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U. S. DEPARTMENT OF AGRICULTURE.

WEATHER BUREAU.

ATMOSPHERIC RADIATION:

A RESEARCH

CONDUCTED AT THE ALLEGHENY OBSERVATORY AND AT PROVIDENCE, R. I.

Submitted to WILLIS L. MOORE, Chief U. S. Weather Bureau,

BY

FRANK W. VERY.

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LETTER OF TRANSMITTAL.

UNITED STATES DEPARTMENT OF AGRICULTURE,
WEATHER BUREAU,
Washington, D. C., January 4, 1900.

Hon. JAMES WILSON,
Secretary of Agriculture.

SIR: I have the honor herewith to transmit for publication, as a bulletin of the Weather Bureau, a memoir by Prof. Frank W. Very on "Atmospheric Radiation."

This paper gives the results of a long research carried on by Professor Very during the past eight years. The expense of the apparatus was defrayed by Prof. James E. Keeler, Director of the Allegheny Observatory, from funds allotted for this purpose by the Hon. J. M. Rusk on the recommendation of my predecessor.

An examination of the manuscript will show that Professor Very has brought to bear upon the study of this important subject a wide range of knowledge and experimental skill acquired by his long service in connection with Prof. S. P. Langley in researches on radiation at the Allegheny Observatory. Professor Very has attacked a problem that has long been recognized as being of fundamental importance in climatology and general meteorology. He has apparently settled some questions that have heretofore been under discussion, but has also raised others for future investigators to discuss.

This memoir is, therefore, to be recognized as one step of progress in our knowledge of the subject of radiation and absorption of heat by the earth's atmosphere, and I take great pleasure in commending it to you.

Very respectfully, your obedient servant,

WILLIS L. MOORE,
Chief United States Weather Bureau.

Approved:
JAMES WILSON,
Secretary of Agriculture.

ATMOSPHERIC RADIATION.

By Frank W. Very.

PREFATORY NOTE.

This research was first suggested in a letter from Prof. Cleveland Abbe, of the United States Weather Bureau, to the writer, dated November 24, 1891, in the course of which he said:

> Absorption *may be* the absolute inverse of *radiation* for gases, but I don't like to assume this as to intensity, and so I beg to know whether you and Professor Keeler can not undertake the following problem: To determine the absolute radiation in calories from a unit mass of gas at given density and temperature and at ordinary temperatures, not when burning, nor when electrified, but when simply heated.
>
> Maurer has given the only determination that I know of, but this is only computed from meteorological observations of cooling at night, and his figures demand confirmation by direct experiment. He finds
>
> σ = coefficient of radiation for air, or the amount of heat in calories that one *unit volume* of air
>
> [at the level of the station where $b = 29.5$ inches; temperature $= 40°$? Fahr.] loses by radiation in unit time (one hour) to a surrounding surface of air whose temperature is 1° lower $= 0.0000418$ gram calories per cubic centimeter per hour. And again from direct radiation observations, he finds 0.000039 calories.
>
> It ought to be possible to determine the quantity and quality of the heat radiated by a mass of warm gas. * * * The stream of gas should be varied as to its diameter, so as to determine the effect of depth from which radiation comes. The ascending flow of warm gas can be kept steady for any length of time or cut off at will. The black surface that serves as the basis for reference should be surrounded by a screen at 0°C., so that it can only receive and transmit or reflect the waves that belong thereto.

In regard to the direct measurement of gaseous radiations of nearly homogeneous quality at moderate temperatures, the following was written in reply (November 27, 1891):

> The problem which you suggest is an exceedingly difficult one. I should anticipate that the radiation from so small a mass of gas as that in a transverse jet would be almost immeasurable, unless at very high temperature. Possibly two long, diaphragmed tubes, surrounded by water jackets, and open at both ends, would answer for ordinary temperatures when interposed in alternation; *e. g.* let temperature of room be $+20°$C., one tube being surrounded by a freezing mixture at $-20°$C., and the other by warm water at $+60°$C. The temperature gradients in the open tubes would be similar and are also determinable.

In commenting on the above suggestion, Professor Abbe expressed the hope that temperatures as low as $-90°$ C. might be attained, but added further the important remark that "the point to be determined experimentally is the law of radiation, transmission, and absorption as depending upon pressure or density of the air rather than as depending upon temperature."

By the advice and consent of Professor Keeler, Director of the Allegheny Observatory, preliminary experiments were commenced in March, 1892, with an apparatus similar to that outlined in the writer's letter of November 27, 1891; but as entire confidence could not be placed in any one method, and as the complete accomplishment of the work contemplated required measurements of atmospheric radiation at various pressures, a more elaborate apparatus was devised with which experiments were begun in 1894 and continued in the intervals between other occupations until the severing of my connection with the Observatory in 1895. The reduction of the observations begun at Allegheny was afterwards continued at Providence, R. I., and required the further consideration of a number of obscure and troublesome details for which I did not find time for several years, but it is hoped that the last of these difficulties has now been successfully met.

The problem has proved much more extensive than I imagined when I first undertook its solution. It is, besides, beset with difficulties. Some of the greatest masters of science have worked at it with only partial success, and with merely qualitative results. Professor Tyndall rightly emphasized the necessity of a long apprenticeship in the methods and manipulations appropriate to this study before one can be ready to appreciate the subtle sources of error to which this particular research is open. The investigator here is dealing with the invisible and the evanescent. In an optical apparatus, a little stray light immediately attracts attention, and we proceed to trace it to its source with our eyes open. In our study of feeble invisible radiations, on the other hand, we grope in the dark, and only succeed in eliminating the unwelcome extraneous rays after innumerable trials and errors.

The final apparatus for work at various pressures frequently gave trouble by springing leaks when heated; and the possibility of contamination of the air column by evaporation or combustion of organic substances prevented the employment of elevated temperatures. Moreover, it was especially desired that the temperatures should not greatly exceed those of the ordinary atmospheric range. Hence the radiations measured have been of small magnitude, requiring a sensitive measuring apparatus, and attention to many minute details inevitable in measurements of this character. I shall not trouble the reader with a recital of all the difficulties encountered; but, in order that the meaning and value of the results may be quite clear, it will be necessary to consider the theory of some parts of the apparatus carefully.

Measuring Instruments.

THE BOLOMETER.

The measurements of radiation have all been made with a bolometer constructed after Langley's earlier plans, in which the exposed face is composed of very thin strips of blackened platinum, arranged in two series, those in the rear occupying the positions of the apertures in the front series. The unexposed member is of nearly identical resistance and is divided into two parts, one on each side of the central member, which receives the radiation coming through the graduated apertures of the bolometer case. The electric current passes to and fro along the strips which are held separate and insulated by grooves in the disk of an ebonite holder, a disposition which is objectionable, as I shall show presently, but which does not prevent the instrument from being used for certain classes of relative measurements, where the accompanying conditions do not vary much.

The bolometer battery consisted of eight gravity cells arranged in one series, the current being reduced to its working strength by interposing resistance between the battery and the Wheatstone's bridge, of which the bolometer forms a part.

When a bolometer of two nearly equal arms is used, it is desirable, in order to secure the most sensitive combination, that the balancing arms of the Wheatstone's bridge should be of greater resistance than the bolometer arms, in case all of the resistances can not be made equal. Since in the bridge used by me, choice could be made between balancing resistances of 1, 10, or 100 ohms, the bolometer arms being a little over 31.5 ohms, at 20° C., or with connections about 32 ohms in all, the normal arrangement of the bridge is with balancing arms of 100 ohms. But on several occasions the bridge, being used for different purposes, was inadvertently left with balancing arms of only 10 ohms. It becomes necessary, therefore, to reduce these measures to normal sensitiveness of a 100 : 32 bridge.

According to theory, the current through the galvanometer is, by Kirchhoff's law:

$$C_5 = \frac{E\,(r_2 r_3 - r_1 r_4)}{D}$$

where

$$D = r_5 r_6 (r_1 + r_2 + r_3 + r_4) + r_5 (r_1 + r_3)(r_2 + r_4) + r_6 (r_1 + r_2)(r_3 + r_4) + r_1 r_3 (r_2 + r_4) + r_2 r_4 (r_1 + r_3).$$

In the normal arrangement (1), and the exceptional or insensitive arrangement (2), the currents in consecutive experiments were:

(1) Measured battery current = 0.026 ampere.
(2) " " " = 0.032 "

The extra resistance (R), plus that of the bridge, was:

(1) $R + \frac{1}{2}(r_1 + r_3) = 266$ ohms.
(2) $R + \frac{1}{2}(r'_1 + r_3) = 221$ "

Assuming the electromotive force of one gravity cell to be 1.1 volt, the total resistance of eight cells, plus an extra resistance of 200 ohms, plus the bridge, should have been:

(1) $$r_6 + R + \tfrac{1}{2}(r_1 + r_3) = \frac{8.8}{0.026} = 338.5 \text{ ohms.}$$

(2) $$r_6 + R + \tfrac{1}{2}(r'_1 + r_3) = \frac{8.8}{0.032} = 275.0 \text{ "}$$

whence the apparent resistance of the battery was:

(1) For eight cells, 72.5 ohms; for one cell, 9.2 ohms.
(2) " " " 54.0 " " " " 6.9 "

According to this, the diminution of the external resistance from 266 to 221, or by 17 per cent., increased the current by 23 per cent., the battery resistance at the same time diminishing by 25 per cent. It is possible that a portion of the change was in the potential of the battery, and both voltage and resistance may have been lower than the values given; but for the purposes of a test, the resistances may be taken as stated, and assuming further that the exposed arm of the bolometer has its resistance increased by radiation by 0.005 ohm, I proceed to calculate the current through the galvanometer in each of the two arrangements of the bridge. The resistances at 20°C. are those of the Elliott coils, graduated according to British Association units, of which 1 = 0.989 of the the accepted legal ohm.

(1) $r_1 = r_2 = 100$, $r_3 = 32.005$, $r_4 = 32$, $r_5 = 20.5$, $r_6 = 272.5$.*
(2) $r'_1 = r'_2 = 10$, $r_3 = 32.005$, $r_4 = 32$, $r_5 = 20.5$, $r'_6 = 254$.

$$D_{(1)} = (20.5 \times 272.5 \times 264.005) + (20.5 \times 132.005 \times 132) + (272.5 \times 200 \times 64.005) + (100 \times 32.005 \times 132) + (100 \times 32 \times 132.005) = 6\,165\,159.$$

$$D_{(2)} = (20.5 \times 254 \times 84.005) + (20.5 \times 42.005 \times 42) + (254 \times 20 \times 64.005) + (10 \times 32.005 \times 42) + (10 \times 32 \times 42.005) = 825\,609.$$

Computed ratio of galvanometer currents:

$$\frac{C_{5\,(1)}}{C_{5\,(2)}} = 1.339 +$$

The theory was tested by exposing the bolometer to radiation from blackened screens containing boiling water, and water at the temperature of the room (about 30° C.) with the following results:

(1) $r_1 = r_2 = 100$ ohms.

Temperature of screens.	Deflection
99°.1	366 div.
29°.4	364
——	367
Excess, 69°.7 C.	367
	364
	362
	365
	363
	363
	361
Mean deflection	=364.2

(2) $r'_1 = r'_2 = 10$ ohms.

Temperature of screens.	Deflection.
99°.1	232 div.
30°.2	232
——	232
Excess, 68°.9	235
	233
	231
	231
	230
	230
	230
Mean deflection	=231.6

* r_6 is supposed to include the extra resistance R.

Galvanometer deflection for 1° of temperature-excess:

(1) 5.225 div. (2) 3.361 div.

Ratio of observed galvanometer currents:

$$\frac{C_5\,(1)}{C_5\,(2)}=1.555$$

To bring the computed value into agreement with the observed, a battery resistance of nearly 1,000 ohms would be required; but this is entirely inadmissible, since any bad connection would have reduced the current and the galvanometer deflection, both of which were such as to give customary values in the normal reduction. For constant battery current the ratio of galvanometer currents with the two arrangements should be:

$$\frac{C_5\,(1)}{C_5\,(2)}=1.339\times\frac{0.032}{0.026}=1.648 \text{ (computed)}$$

$$\frac{C_5\,(1)}{C_5\,(2)}=1.555\times\frac{0.032}{0.026}=1.913 \text{ (observed)}$$

Using the observed factor, observations with insensitive condition of the bridge are brought into fair agreement with normal measures, but the computed factor gives discordant results. There can be no doubt, therefore, of the substantial accuracy of the observed ratio. A study of these discrepancies has elucidated some obscure points in the theory of the bolometer, which I will indicate.

The sensitiveness of a bolometric apparatus is a complex of many factors. It depends upon the resistance of the bolometer, the material of its strips, and the rate at which the metal varies in resistance with changes of temperature, the absorbent quality of the surface for rays of various wave-lengths, the area exposed to radiation, the thickness of the strips, the resistance and form of the galvanometer coils, the strength of the magnets forming the needle, the ratio of their mass to the other parts of the needle, their dimensions and position in reference to the galvanometer coils, the astaticism and damping of the needle, the torsion of its suspending fiber, the strength of the external magnetic field, the arrangement of the Wheatstone's bridge, the strength of battery current employed, and the excess to which the bolometer strips are heated by the current. The last is a very important factor, and is probably responsible for the greater part of the discrepancy between incomplete theory and observation in the preceding example. The theory of the bolometer, in fact, can not be reduced to a simple case of Wheatstone's bridge, unless all of the factors, with the exception of the trifling change of resistance produced by the radiation to be measured, have remained constant.

Prof. Harry F. Reid, in his "Theory of the bolometer" (*Am. Journ. of Sci.*, ser. 3, vol. 35, p. 160, Feb., 1888), has given a formula for the bolometer with its whole surface blackened:

$$\delta=\frac{D\,\alpha\,H}{4}\,\frac{a}{\sqrt{2m}}\,\sqrt{i\,\lambda\,\beta\,(t_1-t_0)}$$

in which δ is the galvanometer deflection, D the galvanometer constant, α the ratio of the resistance of the bolometer strips at the temperature $t_0+1°$ to their resistance at temperature t_0, H the intensity of normal radiation per unit of area expressed in thermal units, a the relative absorbent power of the bolometric surface exposed to radiation, m the loss of heat by combined radiation and convection (conduction being assumed negligible) in thermal units for the unit of time and unit surface of the strips, i the ratio of the resistance of the exposed part of the strips to the entire arm of the Wheatstone's bridge of which they form a part, λ the total length in series of the exposed part of the bolometer strips, β the width of an individual strip, and t_1-t_0 the excess of temperature of the strips due to the battery current which enters as the square root of this quantity, the current being here stated in thermal units, and the galvanometer constant also having reference to these units. The formula also relates to the most efficient arrangement of the bridge resistances, but small variations from this ideal are of minor importance, the main point being that the bolometer arms shall have, as nearly as possible, equal resistances, and be inclosed in a common chamber which can be kept at a nearly constant temperature.

Professor Reid says (p. 165–166):

Since the resistance of the strip does not enter the equation, it is of no importance so long as the four arms of the bridge and the galvanometer all have the same resistance; but this should not be so small as to decrease materially the value of i, or to make the galvanometer connections an appreciable fraction of the resistance in the galvanometer branch. λ and β only occur multiplied together and under the radical sign; other things being equal, δ varies as the square root of the exposable area of the strip. For a given area it does not matter, then, whether the strip be made of a single broad piece of platinum or of several narrow pieces arranged side by side and connected in series. This however, is subject to the limitations mentioned in regard to the resistance of the strip. The thickness of the strip does not occur in the expression above; we have supposed the strip flat and so thin that the edges are only a very small fraction of the surface and the heat lost by conduction negligible. As long as these are true the actual thickness of the strip is unimportant. $(t_1 - t_0)$ is the increase in the temperature of the strip above the case due to the current passing through it; for a particular bolometer it is proportional to the square of the current.

The equation is not of general applicability, and some of the assumptions made in deducing it are not warranted by facts of observation. Thus experiments which I have made, some of which will be described presently, prove that conduction of heat can not be neglected in platinum two or three microns thick, such as is used in bolometers. Again, the relation between the heat generated by the current and the temperature of the strip, deduced "according to Newton's law of cooling, which is sufficiently accurrate for the small change in temperature under consideration," in Professor Reid's estimation, is shown by observation to require a more complex expression, the loss of heat from thin strips being largely produced by convection, which is not nearly proportional to excess of temperature, even though this be small.

In the derivation of the above equation the galvanometer resistance has been assumed equal to that of one arm of the bolometer; but, as shown by Schwendler (*Phil. Mag.* (4), vol. 33, p. 29, 1867), the neglect of the space occupied by insulating material has led to an error in this customary allowance, and Mr. F. A. Laws (*Phys. Rev.*, vol. 5, p. 300, 1897) shows by trials of various windings that in a properly wound galvanometer the galvanometer resistance should be more nearly one-half that of one of the bridge arms if the maximum deflection is required. However, we are not concerned so much with those factors which influence the galvanometer constant as with those which enter into the variable bolometric effect.

The excess of temperature $(t_1 - t_0)$, which in a given bolometer depends mainly on the battery current, varies with the square of the current and inversely as the section of the strip. It is therefore a function of β, the breadth, and θ, the thickness of the strip. But if $\delta \propto \sqrt{\lambda \beta (t_1 - t_0)}$, the substitution of the relation, $t_1 - t_0 \propto \frac{1}{\beta}$, in this variable relation gives:

$$\delta \propto \sqrt{\lambda}$$

and other things being equal. that bolometer which is subdivided into the largest number of strips, or has the largest ratio between λ and β, should give the greatest galvanometer deflection. Possibly this might actually be the case in a vacuum, but in air more than one cause interferes with its realization. To keep the thin metal strips from undesired electric communication an ebonite holder with interlocking grooves has been used in the instrument belonging to my outfit. The heat retained by the nonconducting holder and by impeded convection very nearly neutralizes any gain that might result from the subdivision. But the theory does not yield readily to pure mathematics, and I proceed to experiments which throw some light on the activities in play in a working bolometer.

The measures in the following table were made several years ago by Professor Reid and myself, and were laid aside as hopelessly discrepant; but with further experience I am able to explain the discordances, and to show that they contain the key to a fuller theory of the actual instrument. The experiments were made on a nearly constant source of radiation with a single bolometer, varying the battery current and the aperture in order to get some knowledge of the connection between $\lambda \times \beta$ and $t_1 - t_0$. The quantity $(2\ v)$ is the battery current, given first as originally read in divisions of the arbitrary scale of the battery galvanometer, and afterwards in amperes as corrected by the calibration of the scale. The constant of this galvanometer is 1 div. = 0.000 33 amp. near 100 div., T is the excess of temperature of the radiator. The other symbols are as already defined. The seventh column gives values reduced to uniform battery current and the eighth to full aperture.

TABLE 1.

1	2	3	4		5	6	7	8
i	$\lambda\beta$	T	$2v$		δ	$\frac{\delta}{T}$	$\frac{.033\,\delta}{2vT}$	For aperture of i_1
	sq. mm.	°C.	*div.*	*amp.*	*div.*			
$i_1=0.60$	8.64	81.0	60	$=0.0214$	72.5	0.895	1.383	1.340
$i_1=0.60$	8.64	81.7	82	$=0.0279$	85.2	1.043	1.234	
$i_1=0.60$	8.64	83.7	166	$=0.0480$	157.9	1.886	1.301	
$i_1=0.60$	8.64	82.6	180	$=0.0508$	176.4	2.138	1.388	
$i_1=0.60$	8.64	81.5	196	$=0.0537$	185.4	2.275	1.396	
$i_2=0.38$	5.40	81.1	115.5	$=0.0366$	81.2	1.001	0.902	1.425
$i_2=0.38$	5.40	80.4	126	$=0.0391$	92.2	1.147	0.972	1.536
$i_3=0.25$	3.60	79.9	160	$=0.0467$	77.7	0.972	0.685	1.644
$i_3=0.25$	3.60	79.4	173	$=0.0493$	98.4	1.239	0.832	1.997

The exposed parts of the bolometer strips constitute 62.4 per cent. of the whole, or allowing for the resistance of the connections, 60 per cent. of the total resistance of the bolometeric arm of the Wheatstone's bridge is exposed in condition i_1. The mean currents giving unit deflection per degree of temperature-excess are given in the second column of the next table.

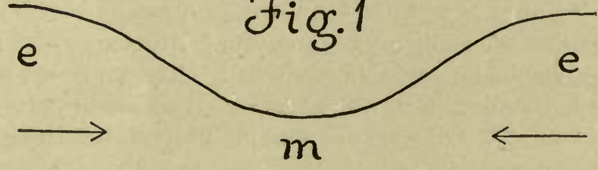
TABLE 2.

Exposed part. i	Battery currents. $2v$	Equally efficient currents $= 2v \times i$
	Ampere.	*Ampere.*
$i_1=0.60$	0.0252	0.01512
$i_2=0.38$	0.0353	0.01341
$i_3=0.25$	0.0434	0.01085

When the aperture of the inner bolometer chamber is reduced, a larger battery current is required to give a constant galvanometer deflection, but a current which is smaller than the inverse proportion of the aperture. The smaller exposed area is therefore more efficient for the unit of battery current, and the reason of this seems to be because the central part of the strips, heated by radiation, are adjoined, in the case of the smaller aperture, by larger portions of free strips at a slightly lower temperature, into which the heat can pass by conduction to be dissipated through a larger surface, but at a lower excess of temperature. One might hesitate to predict whether the larger surface or the lower excess would have the predominating influence, although in general two units of surface radiate less than one unit at twice the excess of the two, and the experiment decides in favor of this view, for the losses are less when the heat is distributed to a relatively wider area, so that a smaller current is then needed to produce a given deflection.

Let a_1 be the area of the fully exposed bolometer strips, a_2, the area of the central part when the aperture of the bolometer chamber is reduced, and Ha_1, Ha_2, the heat received from radiation in the two conditions. Owing to the slight thermal conductivity of the ebonite holder, the heat developed by the current in the covered parts of the bolometer raises the temperature of the ends of the strips excessively, the heat from the covered ends being partly dissipated by conduction to the freely exposed parts, where it passes off by radiation and convection. The distribution of temperature in the shielded strip is therefore something like the curve in fig. 1, the ends (e) being at a higher temperature than the middle (m), and the flow of heat being in the direction of the arrows.

Fig. 1



If c'' is a current larger than c', the excess of temperature of the strips at the ends under these respective currents will be:

$$(t''_1 - t''_o)_e > (t'_1 - t'_o)_e \left(\frac{c''}{c'}\right)^2 \tag{1}$$

while unless conduction more than compensates for the relatively greater loss by radiation and convection at the higher excess, the corresponding quantity in the middle of the strips will be:

$$(t''_1 - t''_o)_m < (t'_1 - t'_o)_m \left(\frac{c''}{c'}\right)^2 \tag{2}$$

and in any case

$$(t_1 - t_o)_e > (t_1 - t_o)_m , \tag{3}$$

the subscript e and m denoting end and middle positions.

During exposure of the central part of a strip to radiation, conduction from the sides in that part must be diminished or reversed. Since the temperature-excess imparted by a given quantity of heat is smaller when the initial temperature is greater, $t_2 - t_1$ must be less at the ends than at the center of the strip, and less at the middle for the greater current; also the mean $t_2 - t_1$, or the mean excess of temperature produced by radiation received, must be less for the fully exposed than for the centrally exposed strip; consequently, λ_1 and λ_2 being lengths of the exposed part of the strips for full and for partial exposure, and the temperature varying symmetrically in the two halves of a strip,

$$\frac{(t_2 - t_1)_e + (t_2 - t_1)_m}{2} < (t_2 - t_1)_m . \tag{4}$$

For the currents c' and c'' the deflections are approximately:

$$\delta'_1 \propto \frac{\sum_o^{\frac{1}{2}\lambda_1} (t_2 - t_1)(\varDelta\lambda)}{\frac{1}{2}\lambda_1} \times (\alpha\, a_1\, c') \tag{5}$$

($\varDelta\,\lambda$ being a small element of length, α the coefficient of change of resistance with temperature)

$$\delta'_2 \propto \frac{\sum_o^{\frac{1}{2}\lambda_2} (t_2 - t_1)(\varDelta\lambda)}{\frac{1}{2}\lambda_2} \times (\alpha\, a_2\, c') \tag{6}$$

$$\delta''_1 \propto \frac{\sum_o^{\frac{1}{2}\lambda_1} (t_2 - t_1)(\varDelta\lambda)}{\frac{1}{2}\lambda_1} \times (\alpha\, a_1\, c'') \tag{7}$$

$$\delta''_2 \propto \frac{\sum_o^{\frac{1}{2}\lambda_2} (t_2 - t_1)(\varDelta\lambda)}{\frac{1}{2}\lambda_2} \times (\alpha\, a_2\, c'') \tag{8}$$

in which

$$\frac{\sum_o^{\frac{1}{2}\lambda_1} (t_2 - t_1)(\varDelta\lambda)}{\frac{1}{2}\lambda_1} < \frac{\sum_o^{\frac{1}{2}\lambda_2} (t_2 - t_1)(\varDelta\lambda)}{\frac{1}{2}\lambda_2}$$

Observation shows that

$$\delta'_1 \div a_1\, c' < \delta'_2 \div a_2\, c' \tag{9}$$

$$\delta''_1 \div a_1\, c'' < \delta''_2 \div a_2\, c'' \tag{10}$$

$$\delta'_1 \div a_1\, c' > \delta''_1 \div a_1\, c'' \tag{11}$$

$$\delta'_2 \div a_2\, c' < \delta''_2 \div a_2\, c'' \tag{12}$$

Hence, within specified limits,

$$\frac{\delta''_1}{a_1\, c''} < \frac{\delta'_1}{a_1\, c'} < \frac{\delta'_2}{a_2\, c'} < \frac{\delta''_2}{a_2\, c''} \tag{13}$$

Inequality (11) is a consequence of the unequal distribution of the temperature-excess developed by the battery current in the strips, and the law of increase of this excess at the preponderant ends, given by (1). Inequality (12), dealing with a part of the strips where temperature is fairly equable, is a consequence, as will be shown presently, of the great influence of convection in cooling, and the rapid rate at which convection increases with the temperature-excess in masses of matter of the form and temperature considered here. Inequality (13) expresses the fact, which has been demonstrated in the experiment already given, that bolometers of reduced aperture are relatively more efficient.

Bolometers used with full aperture, if of the same general construction, are as a rule more efficient per unit of area when the number of strips and the total area are smaller.

Determinations of the battery current required to produce a nearly constant deflection on an approximately constant source of radiation with three different bolometers, constructed with various arrangements of strips, but all having grooved ebonite holders, gave me the results in the next table.

TABLE 3.

(Deflections similar.)

Number of strips in each arm	n	1	5	23
Length of strips exposed	λ	8.5 mm.	48.0 mm.	184.0 mm.
Resistance of bolometer	R	9.2 ohm.	14.7 ohm.	82.1 ohm.
Fraction of resistance exposed	i	0.38	0.60	0.63
Area exposed	$\lambda\beta$	1.62 sq. mm.	8.64 sq. mm.	42.3 sq. mm.
Section of strips	$\beta\theta$	0.000209 sq. mm.	0.000504 sq. mm.	0.000322 sq. mm.
Thickness of strips	θ	0.0011 mm.	0.0014 mm.	0.0028 mm.
Battery current ($2v$) giving uniform deflection		150.5 div. =0.0447 amp.	60.0 div. =0.0214 amp.	13.0 div. =0.0055 amp.
Deflection (mean of 10 observations)	δ	73.4 div.	72.6 div.	75.8 div.
Probable error of 1 observation		±0.63 per cent.	±0.42 per cent.	±0.28 per cent.
Excess of temperature of radiant source	T	82° C.	80° C.	78° C.
Deflection per degree	$\frac{\delta}{T}$	0.895 div.	0.908 div.	0.972 div.
Heat developed by battery-current, computed as proportional to $(2v)^2 R$		7.41	2.71	1.00
Deflection per degree per sq. mm. exposed area		0.552 div.	0.105 div.	0.023 div.
Deflection per degree per mm. of λ		0.1053 div.	0.0189 div.	0.0053 div.
Ratio of efficiency per mm. of λ		19.9	3.6	1.0
Ratio of efficiency per sq. mm. of $\lambda\beta$		24.0	4.6	1.0
Ditto, computed for constant current on erroneous assumption $\delta \propto 2v$		2.934	1.176	1.000

In the next table, further measures, made with the same bolometers by Professor Reid and myself, give a comparison of deflections on a nearly constant source of radiation with approximately constant battery current.

TABLE 4.

(Currents similar.)

Number of strips in each arm	n	1	5	23
Length of strips exposed	λ	8.5 mm.	48.0 mm.	184.0 mm.
Battery current	$2v$	168.0 div.	166.0 div.	157.5 div.
Deflection (mean of 7, 16 and 10 observations)		91.0 div.	157.9 div.	327.2 div.
Probable error of one observation		±0.85 per cent.	±0.44 per cent.	±0.33 per cent.
Excess of temperature of radiant source	T	75°.5 C.	83°.7 C.	78°.4 C.
Deflection per degree		1.205 div.	1.886 div.	4.173 div.
Heat developed by battery current, computed as proportional to $(2v)^2 R$		1.00	1.56	7.85
Deflection per degree per sq. mm. exposed area		0.744 div.	0.218 div.	0.099 div.
Deflection per degree per mm. of λ		0.1418 div.	0.0393 div.	0.0227 div.
Ratio of efficiency per mm. of λ		6.25	1.73	1.00
Ratio of efficiency per sq. mm. of $\lambda\beta$		7.52	2.20	1.00

The relative efficiency of unit area of the bolometer is diminished by the use of an excessive battery current, which evolves so much heat that it can not be dispersed rapidly enough in the rather limited chamber of the bolometer case to prevent undue increase of the primitive excess (t_1-t_0), thereby diminishing the increment (t_2-t_1), due to radiation. A comparison of the relative efficiencies, given in the last lines of Tables 3 and 4, and of the heat developed by the battery current, shows that whereas, with equal currents, the single-strip bolometer is actually about seven and one-half times as efficient as the 23-strip instrument, the heat being nearly eight times as great in the latter, reduction of observations made with unequal currents makes the computed efficiency of the single-strip instrument for equal currents only about three times that of the other, when the heat in the single strip is over seven times as great as in the 23-strip bolometer.

On the other hand, the probable errors of single observations maintain much the same relation when the order of excessive heating by the current is reversed. The deflections with uniform current are by no means inversely proportional to the exposed areas, as the last line of Table 4 shows, the deflection per square millimeter being much greater for the smaller instruments; but this can not be due entirely, or mainly, to diminished values of t_1-t_0 for the smaller, as compared with the larger instruments, for otherwise there should be a reversal of efficiency when the order of excessive heating is reversed, and at least some change in the relation between probable errors.

One other factor remains to be considered—the form of the bolometer. It is evident that a large part of the heat in the strips is removed by convection, and that convection is much impeded in the double-layer, alternate-aperture, gridiron-pattern, or multiple-strip bolometer, while in a single-strip instrument, or one of few and narrow strips, the adherent sheaths of heated air slip from the metal much more readily. The primitive excess of temperature is much less, therefore, in the simpler bolometer, and the excess imparted by radiation is greater. It is difficult to give a mathematical expression for this factor, but the experiments described in the foregoing pages indicate its importance. The removal of hot air by convection is not a perfectly continuous process, but an alternation of instants of quiescence, during which heat accumulates, and the establishment of miniature whirlwinds, by which the hot air is swept away. The irregularities thus produced account for the larger probable errors in those instruments where convection is least impeded. If the battery current is reduced until the probable error for one observation is the same in every case, there is little difference between the deflections from single-strip and multiple-strip bolometers of the same metal.

In the next experiment the mean temperature of excess of the bolometer strips (T), corresponding to (t_1-t_0) in Professor Reid's formula, was calculated, by Callendar's formula* for platinum resistance, from the measured resistances, when different currents (C) were used.

TABLE 5.

Current C.	Temperature excess (T).	$\frac{C^2}{C_2^2}$	$\frac{T}{T_2}$
Ampere.	C. °		
$C_1=0.0011$	$T_1=0.0$	....	....
$C_2=0.0119$	$T_2=0.6$	1.000	1.000
$C_3=0.0279$	$T_3=3.6$	5.497	6.000
$C_4=0.0427$	$T_4=10.4$	12.875	17.333
$C_5=0.0505$	$T_5=15.8$	18.008	26.333

The last two columns show that the mean temperature-excess increases more rapidly than the square of the current, indicating that the confinement of parts of the circuit and the impeding of convection are responsible for the departure.

Returning now to the experiments described on page 7, *et seq.*, the following temperature-excesses are indicated for the bolometer, by the measures in Table 5:

(1) Battery current, $C_1=0.026$ amp., temperature-excess, $T_1=3^\circ.0$ C.
(2) " " $C_2=0.032$ amp., " " $T_2=5^\circ.0$ C.

*$R=1+0.00346\ T$. (See *La Lumière Electrique*, January 8, 1887, p. 78.) Measurements of the resistance of the same bolometer at constant temperatures, in summer and winter, agreed well with this law.

The heat generated by the current in the second case is to that in the first as $(0.032)^2 : (0.026)^2 = 1.515$.

The temperatures maintained are in the ratio: $5.0 : 3.0 = 1.67$.

The ratio for the central part of the strips where the radiation is received, will be smaller than this, as has been pointed out before (inequality 3); but this will not affect the argument, since the diminution of the temperature-ratio is accompanied by an increase of the factor for convection.

A comparison of the loss of heat from thin strips and from the spherical bulb of a small thermometer is instructive. Experiment has shown that the thermometer at corresponding temperature-excesses

$T_1 = 3^\circ.0$, cools $0^\circ.71$ per minute.
$T_2 = 5^\circ.0$, cools $1^\circ.24$ per minute.

The dimensions and water-equivalent of the thermometer bulb were such that these represent, respectively,

0.001032 small calories per sq. cm. per sec.
and 0.001802 " " " " " "

The platinum in one arm of the bolometer had a water-equivalent of about 0.00002 gram, and the heat developed in it by the current was:

(1) $$\left(\tfrac{1}{2} \times 0.026 \times 10^{-1}\right)^2 \times \frac{32 \times 10^9}{4.2 \times 10^7} = 0.00129 \text{ calory per sec.}$$

(2) $$\left(\tfrac{1}{2} \times 0.032 \times 10^{-1}\right)^2 \times \frac{32 \times 10^9}{4.2 \times 10^7} = 0.00195 \quad \text{" " "}$$

The cooling in the two cases must have been:

(1) $$\frac{0.00129}{0.00002} = 64^\circ.5 \text{ per sec.}$$

(2) $$\frac{0.00195}{0.00002} = 97^\circ.5 \quad \text{" "}$$

which, as the temperature-excesses are so much smaller, shows that the strips lose the greater part of their heat in a small fraction of a second. The total area (both sides) of the platinum being about 0.6 sq. cm., the losses are

(1) 0.00215 small calory per sq. cm. per sec.
(2) 0.00325 " " " " " "

taking place partly by radiation through the limited aperture of the ebonite frame holding the strips, and partly by convection from a surface whose ratio to the volume is about 3,000 times as great as that of the thermometer bulb. In the thermometer I have determined the loss by convection as a percentage of the total loss, getting the values in the following table:

TABLE 6.

T.	Convection.	T.	Convection.
°	*Per cent.*	°	*Per cent.*
1	6.5	9	24.8
2	11.0	10	25.8
3	14.5	11	26.7
4	17.0	12	27.4
5	19.2	13	28.0
6	21.0	14	28.6
7	22.5	15	29.2
8	23.7	16	29.8

By the measurements of Dr. J. T. Bottomley* on the emissivity of wires in vacuum and in air, it is evident that, in a wire 0.2 mm. thick at temperature-excesses of 150° and 200° C., con-

* *Phil. Trans. Royal Soc. London*, 1887 (A), p. 429.

vection is about fifty times as great as radiation, which is probably due to the readiness with which successive sheaths of heated air slip off from such a surface. Suppose the thickness of the air sheath to be ten times that of the wire, air to the depth of 2 mm. being heated by molecular interchange. The adhesion between the two must be very slight, but increases with the diameter of the wire.

I have been unable to determine the convective ratio for a bolometer, but it is probably safe to assume that it is intermediate between that of a wire of diameter the same as the width of a single bolometer strip (about 0.2 mm.), and a thermometer bulb. Simply as an illustration, we may suppose the convection ratio is seven times as great as for a bulb. For small excesses, the radiation may be taken proportional to the rise of temperature, and increasing the convection ratios in the preceding table in the proportion 7: 1, we have:

(1) $T_1 = 3^\circ.0$ Radiation + convection $= 1.00 + (7 \times .145 \times 1.00) = 2.015.$

(2) $T_2 = 5^\circ.0$ Radiation + convection $= 1.67 + (7 \times .192 \times 1.67) = 3.914.$

Ratio of total losses $= \dfrac{3.914}{2.015} = 1.942.$

In (2) the temperature being 67 per cent. greater than in (1), the losses are 16.3 per cent. greater than a simple proportion to the losses at the lower temperature, and the rise of temperature produced by a constant radiation is correspondingly less effective in changing the resistance of the bolometer, which may be expressed in terms of galvanometer current by multiplying the computed relative efficiency of the two arrangements of the bridge (p. 7) by 1.163, giving the corrected ratio

$$\frac{C_5\,(1)}{C_5\,(2)} = 1.339 \times 1.163 = 1.557,$$

which is not far from the observed ratio, 1.555, now finally adopted. For equal currents this ratio becomes 1.91, and by this factor all deflections taken with the insensitive arrangement of the bridge have been multiplied.

The value assumed for the convection ratio, according to this test, is slightly too large; but in any case it can not be quite correct, since no allowance has been made for thermal conduction in the thin strips. I am not able at present to give an estimate of this factor, but the following experiment makes its existence probable in metal as thin, or very nearly as thin, as that used for bolometers.

I first heated the front surface of a sheet of platinum, 4 μ thick and blackened on both sides, by radiation from a lamp, and measured the increment of radiation from the rear surface of the platinum by means of a bolometer which was, of course, completely shielded from the direct rays of the lamp. Nearly two minutes were consumed in reaching a maximum deflection. Fearing some secondary effect, due to the gradual heating of the perforated screens which limited the bundle of rays falling on the platinum, the experiment was modified as follows: The sheet of blackened platinum covered the aperture of the bolometer case and was in turn protected by a double cardboard screen with 2-cm. circular apertures centrally situated. A sunbeam of 5.7 cm. circular section, kept fixed by a heliostat, fell upon a concave mirror of 150 cm. focus, and the solar image was formed upon the center of the platinum foil. As before, the radiation from the rear surface of a sheet of platinum, receiving heat from the front by direct radiation on a very small part of its area, was to be measured. The sky was quite clear—the time from 11 to 12 a. m. All exposures were made by withdrawing a distant screen placed in the path of the sunbeam. The results contained in the following table show that much the larger part of the heat, being of course that of the small area embraced in the solar image, is obtained within the first ten seconds. The subsequent progressively diminishing increments can not be attributed to any heating of the bolometer case, since the insertion of a neutral screen behind the platinum made very little change in the deflection.

TABLE 7.

PLATINUM HEATING IN SUNSHINE.

0^s	10^s	20^s	30^s	40^s	50^s	60^s	70^s	80^s	90^s	100^s	110^s	120^s
0	183	193	203	208	213	215	216.5	217.7	217.5	219.0	219.5	220
0	193	204	215	223	228	231	233	234.7	236.3	239.1	238.9	239.1
0	187.4	196.8	205.2	212.6	216	220.6	221.8	223.5	225.4	225.1	224.4	225.6
Mean.	187.8	197.9	207.7	214.5	219.0	222.2	223.8	225.3	226.4	227.7	227.6	228.2
PLATINUM SHADED—COOLING.												
220	49	40	28	19.6	14.4	11.4	8.2	6.0	3.9	2.4	0.8	0
239.1	53	42	29	21	15	11.2	8.3	5.3	3.9	2.2	1.1	0
225.6	49.8	40.7	27.1	18.5	13.1	10.3	7.7	5.3	3.5	1.9	0.4	0
Mean.	50.6	40.9	28.0	19.7	14.2	11.0	8.1	5.5	3.8	2.2	0.8	0

Two minutes are consumed in attaining the maximum radiation, and the same in cooling. The whole of this retardation is not to be attributed to the slowness of conduction in the thin metal. A portion of the effect is due to the time required to establish a heat gradient in the air near the heated strip. The temperature acquired by the thin, blackened platinum in full normal sunshine is such as could be developed by the sun's rays in less than one-tenth of a second if all were absorbed. The same radiation is capable of heating an air layer around the platinum 4.5 mm. deep to the same temperature as the platinum in the same time, and there must be perpetual transfer of heat from the metal to some such layer of air in a bolometer exposed to full sunshine, since more heat is lost by convection than by radiation. How much of the heat in the experiment just described has been transferred from the focus to surrounding parts by conduction, and how much to parts above the focus by convection, can perhaps be determined in a repetition by mapping the distribution of heat in the foil, using a bolometer case of very small angular aperture.

It is evident from the foregoing studies that the thin metal strips of a bolometer had best be supported by stout metal arms at a distance from all insulating or obstructing partitions. Such an instrument has not been used in the present measures, but it is hoped that by keeping the conditions nearly the same, the results may still be capable of statement in terms of absolute measurement.

The actual bolometer used exposes a surface of 19.0 sq. mm., divided into fifteen strips, the total exposed strip-length being

$$\lambda = 15 \times 5.1 = 76.5 \text{ mm.}$$

The methods used in standardizing the instrument will be described under the head of "Screens."

THE GALVANOMETER.

The astatic reflecting galvanometer has a resistance of 20.5 ohms at 20° C. Its chief peculiarity is the needle, which is provided with hollow, cylindrical magnets of very hard steel, arranged in four groups of five each, on opposite sides of a straight, supporting, hollow glass fiber. Each group consists of one magnet 9.5 mm. long, two magnets, each 8.5 mm. long, and two of 6.0 mm. length, arranged symmetrically on pieces of mica, the cylinders being fastened by shellac and kept from contact with each other by minute bits of paper. The magnets are all of one diameter, 1.3 mm., and the weights of the various parts of the needle are as follows:

	mgs.
Twenty hollow cylindrical magnets	219.2
Concave mirror of platinized glass	63.0
Glass fiber (139 mm. long)	32.1
Copper suspension ring	2.0
Mica, paper, and shellac	17.3

In order to balance the mirror, attached to the west face of the upper system, and make the supporting glass fiber hang centrally in its well, a platinum vane, pointing east, was attached at the lower end of the glass fiber, bringing up the total weight of the needle to a little over 350 milligrams.

The rigidity of the needle is sufficient to resist the very slight strain experienced during an ordinary free deflection, but accidental maladjustment has sometimes to be corrected, and the method used in astaticizing may be of interest to those who work with similar instruments.

In a system as delicately constructed as this is, a slight knock or pressure is liable to disturb the parallelism of the planes of the upper and lower systems. Hence, if the upper and stronger

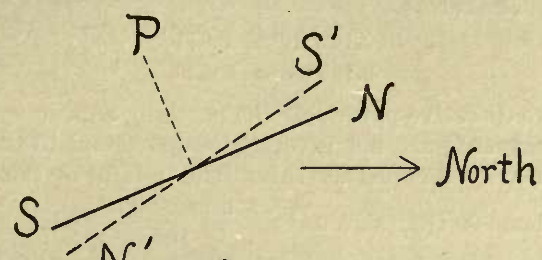


Fig. 2 (Plan)

system, indicated by the full line (NS) in fig. 2, has its plane displaced, so that its north-seeking poles lie on the east side of a vertical plane through the lower system ($N'S'$), there is a resultant magnetism at right angles to the mean plane of the system, and with its north-seeking poles on the east side of that plane. This resultant, combined with the original residual of the partially astatic system, turns the normal to the mirror (P) to the south of the west point. Some care is necessary, therefore, to secure an approach to astaticism and at the same time to keep the mean plane of the system in the magnetic meridian. The following mode of astaticizing has been found advantageous, and, with care, can be applied without dismounting the delicately suspended needle.

The upper system having the greater capacity for retaining magnetism, whatever diminution of magnetism is necessary has been made on this system. The lower system is first magnetized to saturation by a large magnet. Next the magnetism of the upper system is brought to a slight excess by making judicious passes with the large magnet at a distance of 1 cm. or less. Finally, the magnetism of the upper system is diminished very gradually by stroking the individual magnets with minute bits of magnetized needles set in marked wooden handles, the free north-seeking or south-seeking poles projecting slightly.

Suppose that, the normal to the mirror pointing west, the upper system is stroked on its east side by the little magnets.

(1) Strengthening south-seeking poles inclines normal north.
(2) Strengthening north-seeking poles inclines normal south.
(3) Weakening south-seeking poles inclines normal south.
(4) Weakening north-seeking poles inclines normal north.

In case the relative position of the planes has been very much disturbed by these gentle strokings, if, for instance, the normal to the mirror turns strongly to the south after weakening the south-seeking poles of the upper system, it may be necessary to strengthen the south-seeking poles of the lower system by the large magnet; or if the reverse disturbance of the planes has occurred and the normal inclines strongly to the north, the north-seeking poles of the lower system may have to be strengthened. The reasons for the above rules will be evident from the figure. Thus in the application of (3) pressure from the east at S opens the angle between the planes of the system, as in fig. 2. The resultant systems, $N'S$ and NS', are developed, which tend to set in the plane of the meridian. At the same time the directive force of NS has been weakened. In (4) pressure being applied on the east side of N, the opening of the angle between the planes of NS $N'S'$ is the opposite of that in fig. 2, and the resultant magnetic systems, SN', $S'N$, having their south-seeking poles on the east side of the mean plane, tend to rotate P to the north, the directive

force of NS being diminished as before. In (1) the pressure tends to open out the angle as in fig. 2 and swing P to the south, but the directive force of NS being increased, tends in the opposite direction, and it might not be certain which would prevail. The rule, however, is the result of experience.

A single hollow cylindrical magnet 10 mm. long, suspended by a very fine quartz fiber, made a half vibration in 0.286 sec. (specific magetism = 135 C. G. S. units per gram of steel). The average of a system of ten magnets, as prepared for the galvanometer was 0.386 sec. (square = 0.149). In 1892 the astatic condition of the needle was such as to give a half vibration in 10 seconds, which in 1894 had diminished to 8 seconds, no retouching having been made during the interval. The ratios

$$0.149 : 10^2 = 1 : 671$$
$$0.149 : 8^2 = 1 : 429$$

would represent the relative directive powers of the partially astatic system at these dates, were it not that the magnetic moments are not inversely proportional to the squares of the times of vibration in a needle as heavily damped as this. The weight of the magnets being about 0.2 gram, and specific magnetism 800 Gaussian units $\left(\frac{\text{mm.}^{\frac{3}{2}}\ \text{mgr.}^{\frac{1}{2}}}{\text{sec.}}\text{ per mgr. of steel}\right)$, or 80 C. G. S. units per gram of steel, the magnetic moment, if all the magnets pointed one way, would be

$$0.2 \times 80 = 16 \text{ C. G. S.}$$

Astaticized, if the law of inverse squares of the times were followed, the magnetic moments would be

$$(1892) \quad 16 \div 671 = 0.0238 \text{ C. G. S.}$$
$$(1894) \quad 16 \div 429 = 0.0373$$

the ratio of which is

$$0.0238 \div 0.0373 = 0.638.$$

But the galvanometer constant, determined by an entirely independent method, does not differ much from inverse proportionality to the times of vibration, the field magnetization being the same in all cases, a result which is to be attributed to the damping as already noted.

The absolute value of the galvanometer constant, together with a calibration of the galvanometer scale, has been made in the following way: The battery current, measured by an independent standardized galvanometer, was passed through the delicate galvanometer, shunted by 84 cm. of heavy copper wire, 0.494 cm. in diameter, reading the deflections of the sensitive instrument with various extra resistances interposed in the circuit; and the resistances of shunt and battery were determined separately.

The battery resistance was measured by the "half deflection method" in which d_1 being the deflection through extra resistance R_1, d_2 is a deflection, half as great, obtained with extra resistance R_2. The battery resistance is $r = R_2 - (2\ R_1 + G)$, where G is the resistance of the shunted galvanometer, here practically zero. Three trials gave:

$d_1 = 500$ div.,	$R_1 = 460$ ohms,	$d_2 = 250$ div.,	$R_2 = 204$ ohms,	$r = 52$ ohms.
$d_1 = 400$ "	$R_1 = 584$ "	$d_2 = 200$ "	$R_2 = 258$ "	$r = 68$ "
$d_1 = 300$ "	$R_1 = 794$ "	$d_2 = 150$ "	$R_2 = 369$ "	$r = 56$ "

Average battery resistance = 59 ohms.

The resistance of the shunt was measured by short-circuiting it by a plug, when the very low resistance of the heavy brass connections of the resistance box became the sole shunt, reducing the galvanometer deflection almost to zero. The current from a single cell of gravity battery, reduced by 1,100 ohms, was passed directly through the galvanometer thus shunted, the galvanometer connections being opened and closed by a key. The valuation of the deflections was made by repeating with shunt short-circuited, and either of the smaller (hundredth and fiftieth ohm) coils in its place, using the formula for shunts:

$$\frac{C_1}{C} = \frac{S}{S + G}$$

where C_1 is the current through the galvanometer, C the total current, S the resistance of the

shunt, and G that of the galvanometer. In the present case, however, since S is very small relatively to G, the ratio $\frac{S}{S+G}$ is substantially equal to $\frac{S}{G}$, which may be used instead.

Putting in the plug also short-circuits the thermopile currents from junctions of unlike metals, and changes of temperature cause these to vary, but by reversing the galvanometer connections, their effects may be partly eliminated. With a high-resistance galvanometer this trouble would cease.

Galvanometer connections, direct or reversed, are denoted by *d* and *r* in the following table. Shunt, open or plugged (that is, short-circuited), is signified by *o* and *p*. The comparison deflections, in the last column but one, correspond to a hundredth-ohm coil, and to half the deflections given by two different fiftieth-ohm coils.

TABLE 8.

Plugged.	Open.	Plugged.	Shunt.	Plugged.	Open.	Plugged.	Shunt.	0.01 ohm.	Res. shunt.
rp	*ro*	*rp*		*dp*	*do*	*dp*			
div.	*div.*	*div.*	*div.*	*div.*	*div.*	*div.*	*div.*	*div.*	*ohm.*
— 3.0	—15.0	— 3.0	— 17.9	+22.5	+33.1	+20.4	+ 35.4	162.9	$\frac{13.6\times0.01}{163}$
— 2.7	—18.2	— 7.0		+20.0	+35.5	+21.2		153.2	
— 4.1	—20.6	— 6.0	—(—4.3)	+21.8	+37.6	+18.8	— 20.8	172.0	
— 3.3	—17.9	— 5.3	— 13.6	+21.4	+35.4	+20.1	+ 13.6	162.7	=0.00083
dp	*do*	*dp*		*rp*	*ro*	*rp*			
+11.7	+36.9	+15.2	+ 34.6	+ 2.9	—20.0	— 5.2	— 20.4	133.4	$\frac{19.3\times0.01}{145}$
+12.4	+33.0	+18.0		+ 1.2	—19.2	— 4.8		142.1	
+13.5	+33.8	+18.7	— 14.9	+ 1.6	—22.0	— 3.7	— (—1.4)	159.5	
+12.5	+34.6	+17.3	+ 19.6	+ 1.9	—20.4	— 4.6	— 19.0	145.0	=0.00133
Heavy copper shunt reversed and solidly clamped.									
dp	*do*	*dp*		*dp*	*do*	*dp*			
+11.0	+26.6	+13.9	+ 29.0	+13.9	+34.0	+21.0	+ 32.3	122.1	$\frac{15.2\times0.01}{144}$
+ 9.9	+31.5	+15.2		+15.2	+31.0	+20.3		118.6	
+11.5	+29.0	+15.5	— 12.9	+15.5	+31.9	+21.8	— 18.0	147.8	
								147.8	
								162.8	=0.00109
+10.8	+29.0	+14.9	+ 16.1	+14.9	+32.3	+21.0	+ 14.3	163.8	
rp	*ro*	*rp*		*rp*	*ro*	*rp*			
— 3.2	—20.0	— 5.0	— 21.5	—12.0	—31.2	—20.9	— 31.9		$\frac{16.3\times0.01}{144}$
— 2.0	—23.2	— 7.5		—16.0	—33.0	—17.2			
— 2.5	—21.2	— 6.2	—(—4.4)	—13.6	—31.4	—19.1	—(—16.5)		
— 2.6	—21.5	— 6.2	— 17.1	—13.9	—31.9	—19.1	— 15.4	143.8	=0.00113
Mean resistance of heavy shunt .... =0.00109									

In the galvanometer tests, induction currents gave a stronger backward swing than happens in the bolometric work where there is a continuous current only slightly varied by the resistance changes due to radiation. Consequently deflections have been computed by a formula:

$$\delta = d - \frac{e_1 + e_2}{2}$$

where e_1 is the reading before connecting, d the extreme of the swing given by the current, and e_2 is obtained from three successive swings of the needle, after the current is broken, by the formula:

$$e_2 = \frac{n_2^2 - n_1 n_3}{2n_2 - n_1 - n_3}$$

A single series follows in full (extra resistance, 270 ohms).

TABLE 9.

e_1	d	n_1	n_2	n_3	e_2	$\frac{e_1+e_2}{2}$	δ
+2	+405	−111	+35	−3	+4.9	+3.5	+401.5
0	403	−117	+30	−5	+1.7	+0.9	402.1
+1	397	−116	+30	−5	+1 8	+1.4	395.6
0	389	−114	+29	−6	+0.9	+0.5	388.5
+1	389	−115	+26	−7	−0.7	+0.2	388.8
0	388	−113	+30	−6	+1.2	+0.6	387.4
+1	395	−115	+31	−3	+3.4	+2.2	392.8
−1	396	−118	+27	−9	−1.8	−1.4	397.4
−1	396	−113	+33	−2	+4.8	+1.9	394.1
+2	396	−111	+30	−4	+2.6	+2.3	393.7
+0.5	+395.4	−114.3	+30.0	−5.0	+1.9	+1.2	+394.2

The ratio of the current in the galvanometer to that in the shunt is taken as 1:18,800. The mean results of five series are given.

TABLE 10.

Series.	Extra resistance plus battery.	Current in shunt.	Deflection. δ	Current in galvanometer.	Galvanometer constant. 1 div. =
	Ohms.	*Ampere.*	*Divisions.*	*Ampere.*	*Ampere.*
1	1,159	0.00735	114.7	3.91×10^{-7}	3.40×10^{-9}
2	609	0.01399	211.6	7.44	3.51
3	429	0.01986	298.5	10.56	3.53
4	329	0.02590	394.2	13.78	3.50
5	269	0.03167	484.2	16.85	3.48
Mean galvanometer constant, 1 div. $=3.48\times10^{-9}$ ampere.					

It will be seen that the galvanometer constant is the same in all parts of the scale, as nearly as can be determined by this method. There have been some indications that the instrument is a very little more sensitive for small deflections, less than 20 div.; but as the amount is hardly appreciable, and seems to vary with the slightest change in the hanging of the needle, no correction has been applied.

Since the cylindrical magnets do not lie in the central plane of the coils, the induction damping is larger than usual, and departure from a logarithmic decrement was to be anticipated in the vibrations. The means of the five series, similar to that given in full in Table 9, are:

TABLE 11.

e_1	d	n_1	n_2	n_3	e_2	$\frac{e_1+e_2}{2}$	δ
+0.3	+115.1	− 31.2	+ 8.6	−1.7	+0.5	+0.4	+114.7
+0.2	+211.7	− 60.3	+15.5	−4.1	±0.0	+0.1	+211.6
−0.2	+298.9	− 86.3	+23.3	−4.9	+1.0	+0.4	+298.5
+0.5	+395.4	−114.3	+30.0	−5.0	+1.9	+1.2	+394.2
+0.6	+484.0	−141.6	+34.6	−9.3	−0.9	−0.2	+484.2

The next table contains the amplitudes (a_1 a_2 a_3) of successive vibrations and the logarithms of their ratios.

TABLE 12.

a_1	a_2	a_3	$log\ \frac{a_1}{a_2}$	$\frac{1}{2}\ log\ \frac{a_1}{a_3}$
146.3	39.8	10.3	0.5651	0.5766
272.0	75.8	19.6	0.5550	0.5713
385.2	109.6	28.2	0.5560	0.5678
509.7	144.3	35.0	0.5460	0.5816
625.6	176.2	43.9	0.5503	0.5769
Mean logarithmic decrements.			0.5545	0.5749

The air damping appears to be tolerably uniform, since there is no marked relation between the logarithmic decrements and the amplitudes; but the influence of induction currents is seen in the change of the decrement in successive periods.

The needle is suspended by a single fiber of silk, 33 cm. long from the suspending piece to the copper ring. The entire fiber is about 40 cm. long, is tied to the copper ring of the needle by a loose square knot, and, at its other end, carries a weight equal to that of the needle. At the outset the galvanometer is inverted, and the counterpoise hanging freely, the silk fiber is allowed to stretch and untwist until it comes into a normal state; then the galvanometer is set up in its usual position, the fiber passing over the edge of the suspending piece, but not being fastened to it. The suspending piece is finally adjusted until the needle hangs centrally. As thus prepared the silk fiber has very little tendency to twist, the image from the free but undisturbed needle seldom wandering during the day more than the few divisions to be expected from the diurnal variation of the magnetic declination.

The bolometric equilibrium can not be maintained perfectly in a room of changing temperature, and some means of bringing the null point to any part of the scale at pleasure is desirable. Variation of the field by weak magnets, although objectionable, has been used to some extent. The change of field necessary in order to push the null point from one end of the scale to the other was determined by measuring the deflection from a constant impulse.

TABLE 13.

Starting point.	Mean of 10 deflections.	Percentage of deflection at 100.
Divisions.		*Per cent.*
0	+87.61±0.34	101.9
100	+85.03±0.38	100.0
200	+84.99±0.39	98.1
300	+81.27±0.51	96.1
400	+80.83±0.72	94.3

In order that the deflections may be comparable within 2 per cent., the null point should not be changed by more than 100 divisions during the observations. To avoid the necessity of more than a slight change of field the electric current has been allowed to flow through the bolometer for at least twenty-four hours before commencing observations, and the room has been kept at a nearly constant temperature.

The cover glass of the galvanometer case has optically plane parallel surfaces, and the carefully figured mirror gives a sharp image, permitting readings by estimation to a tenth of a division.

In some of the experiments I have made the exposure to radiation by pulling cords, at the same time reading the galvanometer; in others, it has been necessary to have an assistant shift some part of the apparatus at the word of command.

SCREENS.

The bolometer chamber has been used with two different openings: First, a wide aperture, limited by a series of graduated circular card-board diaphragms, the outermost 1.19 inches (3.02 cm.) in diameter, 3.92 inches (9.96 cm.) from the bolometer, giving an angular aperture of 17° 16′. Second, a smaller aperture, the case being further protected by triple tin-plate screens, with circular openings: the outermost 1.15 inches (2.92 cm.) in diameter, 12.3 inches (31.24 cm.) in front of the bolometer (angle 5° 21′); the middle and limiting aperture 1.02 inches (2.59 cm.) in diameter, 11.3 inches (28.70 cm.) from the bolometer, giving an angular aperture of 5° 10′.

The ratio of the squares of the angular apertures is 11.17 : 1, but the observed efficiencies have the ratio 8.96 : 1, which is adopted. I can only conjecture that the difference is due to the reflection of the bolometer's radiation by the polished tin plate, and the retention of a larger proportion of the heat received from radiation when the aperture is partly closed by the metal screen; but no experiments have been tried to test the hypothesis.

In order to transform the measures made in arbitrary units of a scale into absolute units of radiant energy, and at the same time to furnish a check on the constancy of the measuring instruments, the bolometer has been exposed from time to time to the radiation from blackened copper screens containing water at different temperatures.

The unit of radiant energy employed is that which I have elsewhere called the *radim*,* "representing a unit quantity of heat, namely, one gram-water-degree-centigrade heat-unit, lost *as radiation* per square centimeter of surface per second of time, by a heated body, or transmitted by the ether as an equivalent amount of radiant energy through a normal section of 1 sq. cm. in one second of time."

The standard of radiation adopted is that of blackened copper at 100° C. to a surface of the same material at 0° C., filling the hemisphere, which, according to the measures of Dr. J. T. Bottomley may be taken as 0.0126 radim. Measured radiations between any other temperature limits have been reduced to the standard by multiplying by a factor obtained by dividing the difference of radiations at the given limits, as read from the standard curve (derived from Table B, p. 270, *Astrophysical Journal*, Vol. 8), by 0.0126. The deflections are further reduced to a standard battery current of 0.033 ampere, corresponding to 100 div. of the battery galvanometer.

The radiating surface, seen through the full aperture of 17° 16′, occupied

$$(50 \times \tan 8^\circ 38')^2 \times \pi = 181.06 \text{ sq. cm.},$$

the center of the radiating surface being placed 50 cm. from the bolometer, and its plane normal to the line of sight. The mean angle with the line of sight of a circle in the radiating surface at mean distance is

$$\alpha = \tan^{-1} \frac{r\sqrt{2}}{2 \times 50} = 6^\circ 7'.7,$$

where the radius of the bounding circle is

$$r = 50 \times \tan 8^\circ 38';$$

and the mean distance of the surface is

$$d = \frac{r\sqrt{2}}{2 \sin \alpha} = 50.319 \text{ cm.}$$

The bolometer of 0.19 sq. cm. receives of the total radiation, assuming equable emission at all inclinations, the fraction

$$\frac{0.19}{2\pi d^2} = 0.000\ 011\ 957$$

and the standard radiation received by the bolometer with full aperture is

$$E_1 = 0.000011957 \times 181.06 \times 0.0126.$$

$$= 0.000\ 027\ 278 \text{ radim.}$$

The smaller aperture has been used with radiators but little removed. The radiation through

* The Probable Range of Temperature on the Moon, *Astrophysical Journal*, vol. 8, p. 271, December, 1898.

this aperture, of 1.295 cm. radius, is virtually that of a surface of like area, 5.2685 sq. cm., and the standard radiation received by the bolometer is

$$E_2 = \frac{0.19}{2\,\pi \times (28.7)^2} \times 5.2685 \times 0.0126.$$

$$= 0.000\ 002\ 437 \text{ radim.*}$$

The efficiency of the radiation coming through this smaller aperture, however, has been shown to be 25 per cent. greater than that of an equal amount of radiant energy passing through the large aperture (p. 21).

I proceed to give screen comparisons and the valuation of standard deflections.

March 12, 1892.

FIRST SERIES.

Battery galvanometer 100 div.
Hot screen 69°.8 C., computed radiation 0.0154 radim.
Cold " 9°.5 C., " " 0.0083 "
Radiation reduced from standard:

$E = E_2 \times \frac{71}{126} = 0.000\ 001\ 373$ radim.

$\delta = 35.43$ div. (mean of 10, small aperture); 1 div. = 0.000 000 0388 radim.

Standard deflection, on standard radiation, and with full aperture $= 35.43 \times 8.96 \times \frac{126}{71} =$ 563.4 div.

SECOND SERIES.

Battery galvanometer 100 div.
Hot screen 69°.4 C., computed radiation 0.0153 radim.
Cold " 11°.8 C., " " 0.0085 "

$E = E_2 \times \frac{68}{126} = 0.000\ 001\ 315$ radim.

$\delta = 30.94$ div. (mean of 10, small aperture); 1 div. = 0.000 000 0425 radim.

Standard deflection (full aperture) $= 30.94 \times 8.96 \times \frac{126}{68} = 513.7$ div.

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* The quantities E_1 and E_2 are introduced purely as reduction factors, and do not represent exactly the quantities of *normal* radiation received by the actual bolometer, although the latter may easily be derived from them.

The total radiation from each unit of radiating surface to a hemisphere is to the fraction of radiation emitted per sq. cm. at angle (i_1) with the normal, and received on an element of the hemisphere (δs), in the p.oportion

$$2\,\pi\,r \times \sum_0^{\frac{1}{2}\pi} \cos i \sin i\,\delta i \;:\; \cos i_1\ \delta s.$$

In the present case, cos i_1 may be taken as unity, δs (the area of the bolometer) is 0.19 sq. cm., $\delta i = \frac{1}{2}$ degree, and $r = 28.7$ cm.

The numerical value of

$$2\,\pi\,r \times \sum_0^{\frac{1}{2}\pi} \cos i \sin i\,\delta i = \pi\,r \sum_0^{\frac{1}{2}\pi} \sin 2i \times \frac{\pi\,r}{360}$$

is 2587.7, and the bolometer receives $0.19 \div 2587.7 = \frac{1}{13619}$ of the entire radiation.

For any other radiator than lampblack, the relative radiation, $\rho \times \phi(i)$, must be considered. The value of ρ has been determined for air in the present research for nearly normal emission, but $\phi\,(i)$ remains unknown.

July 28, 1892.

Battery galvanometer 97 div.
Hot screen 76°.0 C., computed radiation 0.0162 radim.
Cold " 33°.8 C., " " 0.0107 radim.

$$E = E_2 \times \frac{55}{126} = 0.000\ 001\ 073 \text{ radim.}$$

$$\delta = \frac{24.54 \times 100}{97} = 25.30 \text{ div. (mean of 10, small aperture); 1 div.} = 0.000\ 000\ 0424 \text{ radim.}$$

$$\text{Standard deflection (full aperture)} = 25.30 \times 8.96 \times \frac{126}{55} = 519.3 \text{ div.}$$

March 10, 1893.

Battery galvanometer 98 div.
Hot screen 99°.0 C., computed radiation 0.0200 radim.
Cold " 0°.8 C., " " 0.0078 "

$$E = E_1 \times \frac{122}{126} = 0.000\ 026\ 412 \text{ radim.}$$

$$\delta = 515.9 \times \frac{100}{98} = 526.4 \text{ div. (mean of 10, full aperture); 1 div.} = 0.000\ 000\ 0502 \text{ radim.}$$

$$\text{Standard deflection (full aperture)} = 526.4 \times \frac{126}{122} = 543.7 \text{ div.}$$

March 3, 1894.

Battery galvanometer 101 div.
Hot screen 98°.7 C., computed radiation 0.0200 radim.
Cold " 0°.7 C., " " 0.0078 "

$$E = E_1 \times \frac{122}{126} = 0.000\ 026\ 412 \text{ radim.}$$

$$\delta = \frac{487.4 \times 100}{101} = 482.6 \text{ div. (mean of 10, full aperture); 1 div.} = 0.000\ 000\ 0547 \text{ radim.}$$

$$\text{Standard deflection (full aperture)} = 482.6 \times \frac{126}{122} = 498.4 \text{ div.}$$

March 30, 1894.

Battery galvanometer 95 div.
Hot screen 99°.1 C., computed radiation 0.0200 radim.
Cold " 29°.4 C., " " 0.0103 "

$$E = E_1 \times \frac{97}{126} = 0.000\ 021\ 000 \text{ radim.}$$

$$\delta = 364.2 \times \frac{100}{95} = 383.4 \text{ (mean of 10, full aperture); 1 div.} = 0.000\ 000\ 0548 \text{ radim.}$$

$$\text{Standard deflection (full aperture)} = 383.4 \times \frac{126}{97} = 498.0 \text{ div.}$$

July 30, 1895.

Battery galvanometer 95 div.

First Series.

Hot screen 98°.3 C., computed radiation 0.0198 radim.
Cold " 23°.7 C., " " 0.0097 "

$$E = E_1 \times \frac{101}{126} = 0.000\ 021\ 866 \text{ radim.}$$

$$\delta = 456.1 \times \frac{100}{95} = 480.1 \text{ (mean of 10, full aperture); 1 div.} = 0.000\ 000\ 0456 \text{ radim.}$$

$$\text{Standard deflection (full aperture)} = 480.1 \times \frac{126}{101} = 598.9 \text{ div.}$$

SECOND SERIES.

Hot screen 91° C., computed radiation 0.0187 radim.
Cold " 24° C., " " 0.0097 "

$E = E_1 \times \frac{90}{126} = 0.000\ 019\ 484$ radim.

$\delta = 401.7 \times \frac{100}{95} = 422.8$ (mean of 5, full aperture); 1 div. = 0.000 000 0461 radim.

Standard deflection (full aperture) $= 422.8 \times \frac{126}{90} = 591.9$ div.

THIRD SERIES.

Hot screen 85° C., computed radiation 0.0177 radim.
Cold " 24° C., " " 0.0097 "

$E = E_1 \times \frac{80}{126} = 0.000\ 017\ 319$ radim.

$\delta = 354.8 \times \frac{100}{95} = 373.5$ (mean of 5, full aperture); 1 div. = 0.000 000 0464 radim.

Standard deflection (full aperture) $= 373.5 \times \frac{126}{80} = 588.3$ div.

FOURTH SERIES.

Hot screen 77° C., computed radiation 0.0164 radim.
Cold " 24° C., " " 0.0097 "

$E = E_1 \times \frac{67}{126} = 0.000\ 014\ 505$ radim.

$\delta = 300.6 \times \frac{100}{95} = 316.4$ (mean of 5, full aperture); 1 div. = 0.000 000 0458 radim.

Standard deflection (full aperture) $= 316.4 \times \frac{126}{67} = 595.0$ div.

The last four series were made to test the validity of the mode of reduction for E, which is sufficiently accurate for its purpose. The two series of March 12, and that of July 28, 1892, being founded on rather small deflections taken with the small aperture, are less reliable than the others. They give a mean value of 1 div. = 0.000 000 0412 radim, corresponding to 0.000 000 0412 $\times \frac{5}{4}$ = 0.000 000 0515 radim for the full aperture. The observation of March 10, 1893, with full aperture, gave 1 div. = 0.000 000 0502 radim, and the galvanometer constant may be assumed uniform for the first year (1892–93), when its value in amperes was measured. On March 3, and March 30, 1894, larger radiation was required to give a deflection of one division, namely, 1 div. = 0.000 000 0548 radim, or 7½ per cent. greater than in 1892–93, the vibration of the needle having meanwhile become 20 per cent. more rapid, or the squares of the times 36 per cent. smaller; and finally, in July, 1895, the time of vibration being the same as in 1894, 1 div. = 0.000 000 0460 radim, or 7½ per cent. less than in 1892–93. The last change is perhaps attributable to simultaneous changes in the magnetism of the needle and in the magnetic field, but as the field was not measured independently, no correction is available.

The variation of the radiator's surface is a possible source of error in these standardizings. To guard against it, a uniform procedure has been followed. The screens are of copper, painted dead black, with a very thin coat. Before using, this surface is lightly smoked with a fresh coat of soot, uniformly distributed. From experience with such a surface, it does not seem probable that variations of more than 2 or 3 per cent. are to be anticipated; but it is not asserted that this standard fulfilled the ideal of an absolutely black body. After the measures of July 30, 1895, an effort was made to carry the radiant emissivity of the hot screen somewhat nearer its maximum value, by repeated smokings, while the screen was temporarily filled with cold water, until a coat of soot ½ mm. thick had been deposited. The mean standard deflection of 593.5 was thereby raised to 620.7, or by 4.6 per cent.

If the variations are attributed to errors, and all observations have equal weight, 1 div. = 0.000 000 0490 ± 0.000 000 0010 radim, but in the author's opinion, it is best to accept the variation as a fact and to take the valuations as given at the stated epochs, whence, for full aperture, we have the following radiant values:

(1892–93)	1 div. =	0.000 000 0509 radim.
(1894)		0.000 000 0548 "
(1895)		0.000 000 0460 "

For the small aperture, the corresponding values are four-fifths of these—

(1892–93)	1 div. =	0.000 000 0412 radim.
(1894)		0.000 000 0438 "
(1895)		0.000 000 0368 "

PSYCHROMETER FACTOR.

The water-vapor in the air experimented upon has been measured by a stationary psychrometer, checked occasionally by a dew-point apparatus. The usually adopted formula for a ventilated or a sling psychrometer is:

$$f_1 = f_2 - 0.000\ 67\ (t - t')\ H,$$

where f_1 = the pressure of water-vapor at the dew-point, f_2 = the vapor pressure at the temperature of the wet bulb, and H = the barometer reading, may be in either millimeters or inches of mercury; but t and t', the dry and the wet-bulb readings, are in centigrade degrees.

The statement is made in books on the subject that the numerical factor by which the difference $(t - t')$ is to be multiplied, may need to be doubled in a closed room; but since every psychrometer must vary according to the kind of muslin with which the wet bulb is covered, and according to the disposition of objects around it, the factor should be determined by experiment.

Two windows on opposite sides of the room were left open, producing a gentle circulation of the air. Dew was formed on a polished tin-plate vessel in which water was cooled by ice, or heated at pleasure. The cold water half filled the vessel, and the contrast between upper and lower halves was noted.

(1)

$$\begin{array}{lr} & ^\circ C. \\ \text{Dew formed at} & +6.8 \\ \text{Dew evaporated at} & +9.4 \end{array}\Bigg\}\ \text{Mean}\ \begin{array}{r} ^\circ C. \\ +8.1 \end{array}$$

(2)

$$\begin{array}{lr} & ^\circ C. \\ \text{Dew formed at} & +7.8 \\ \text{Dew evaporated at} & +8.9 \end{array}\Bigg\}\ \text{Mean}\ \begin{array}{r} ^\circ C. \\ +8.4 \end{array}$$

Observed dew-point = + 8°.3 C. = +46°.9 F.

Corresponding psychrometer readings:

(1)

$$\begin{array}{lrcr} & ^\circ F. & & ^\circ C. \\ \text{Dry bulb} & 77.1 & = & 25.0 \\ \text{Wet bulb} & 63.2 & = & 17.3 \end{array}\Bigg\}\ \text{Difference}\ \begin{array}{rcr} ^\circ F. & & ^\circ C. \\ 13.9 & = & 7.7 \end{array}$$

(2)

$$\begin{array}{lrcr} & ^\circ F. & & ^\circ C. \\ \text{Dry bulb} & 77.6 & = & 25.3 \\ \text{Wet bulb} & 63.7 & = & 17.6 \end{array}\Bigg\}\ \text{Difference}\ \begin{array}{rcr} ^\circ F. & & ^\circ C. \\ 13.9 & = & 7.7 \end{array}$$

The windows were now closed.

(In ten minutes.)

(3)

$$\begin{array}{lrcr} & ^\circ F. & & ^\circ C. \\ \text{Dry bulb} & 78.8 & = & 26.0 \\ \text{Wet bulb} & 66.4 & = & 19.1 \end{array}\Bigg\}\ \text{Difference}\ \begin{array}{rcr} ^\circ F. & & ^\circ C. \\ 12.4 & = & 6.9 \end{array}$$

(In thirty minutes.)

(4)

	°F.	°C.		°F.	°C.
Dry bulb	79.9	= 26.6	Difference	11.4	= 6.3
Wet bulb	68.5	= 20.3			

(In sixty minutes.)

(5)

	°F.	°C.		°F.	°C.
Dry bulb	80.1	= 26.7	Difference	12.0	= 6.7
Wet bulb	68.1	= 20.0			

Open windows.

By Hazen's Tables (Fahrenheit, p. 64) for the temperature 77° F. and dew-point 47°, the depression of the wet bulb (ventilated) is 17°.25 F. The observed depression was 13°.9 F., whence $(t-t')$ must be multiplied by

$$\text{factor} = \frac{17.25}{13.9} = 1.24$$

For the temperature 77°.5 F. (same dew-point), the depression by the table is 17°.50 F., and the observed depression 13°.9 F.

$$\text{factor} = \frac{17.50}{13.9} = 1.26$$

Windows closed.

For the temperature 79° F. (same dew-point as before), by table, depression = 18°.5 F., observed, 12°.4,

$$\text{factor} = \frac{18.5}{12.4} = 1.49$$

For the temperature 80° F. (same dew-point), by table, depression = 19°.0 F., observed, 11°.4,

$$\text{factor} = \frac{19.0}{11.4} = 1.67$$

For the temperature 80° F. (same dew-point), the final observation gave depression 12°.0,

$$\text{factor} = \frac{19.0}{12.0} = 1.58$$

The first condition (two windows open) is seldom realized in bolometric work, and never unless the outside air is nearly calm, which was not the case during the above experiments. In winter the windows are usually closed during bolometric observations, this being necessary to prevent air currents and sudden variations of temperature around the bolometer. The room in which the experiments were made has a floor space of 60 sq. m., and is connected with other rooms, all heated by a hot-air furnace, and well ventilated. In warm summer weather a single window is commonly open. These things being so, since the mean of the above determinations gives 1.45 for the multiplier, 1.5 is adopted as the working factor by which $(t - t')$ has been multiplied in finding the dew-point by the unventilated psychrometer, and by Hazen's Tables. With this explanation, further details will be omitted, and only the results of psychrometric measures will be stated.

Three successive pieces of apparatus have been used for measures of atmospheric radiation:

(*a*) A pair of open radiant cylinders.
(*b*) Hot air ascending from a furnace flue.
(*c*) A closed radiant cylinder with movable disk.

The horizontal air column in line with the bolometer is to be considered as composed of two parts. The portion between the bolometer and the front of the radiating apparatus is of nearly the same temperature as the bolometer, and acts chiefly by absorbing. The portion of air within the apparatus both radiates and absorbs, but the differential effect is radiative, and for the sake of distinction the first part may be called the absorbent, the second the radiant layer.

Psychrometer readings, as usually reduced, are stated in pressures of water-vapor on the standard of the mercury gage (millimeters of mercury), or as a weight of water per unit volume of air (grams per cubic meter); but in considering the absorbent or radiant effects it is more convenient to express the amount of water-vapor as a depth of equivalent liquid water penetrated by the line of sight within the limits of the radiative or absorbent column. For example, a column of air 100 meters long and 1 square decimeter in section occupies 1 cubic meter, and if its water-vapor be all condensed upon a normal section, a liquid layer 1 millimeter thick will be produced for every 10 grams of vapor contained in the air column. If the volume of air has the form of a cube 1 meter on an edge, the layer of condensed water being distributed over a normal section of 1 square meter, will have a depth of 0.01 mm. for every 10 grams per cubic meter, the depth of water being directly proportional to the length of the air column multiplied by the absolute humidity. This mode of expression relates solely to the quantity of water present. Nothing is predicated as to the quality of its absorption or radiation, which may vary widely according to the physical state in which this definite quantity of water exists.

The chief atmospheric constituent affecting radiation being water-vapor, it is necessary to consider the air depths (d), and the equivalent layers of liquid water (w) in d, for each gram of water-vapor per cubic meter of air, involving the following constants in the successive pieces of apparatus.

TABLE 14.

	Absorbent layer.	Radiant layer.
Apparatus a	d = 13.2 inches = 33.5 cm. w = 0.000 0335 cm.	36.4 inches = 92.5 cm. 0.000 0925 cm.
Apparatus b_1	d = 10.0 inches = 25.4 cm. to 7.0 inches = 17.8 cm. w = { 0.000 0254 cm. 0.000 0178 cm.	16.0 inches = 40.6 cm. 0.000 0406 cm.
Apparatus b_2	d = 16.25 inches = 41.2 cm. to 11.5 inches = 29.2 cm. w = { 0.000 0412 cm. 0.000 0292 cm.	3.5 inches = 8.9 cm. to 7.0 inches = 17.8 cm. { 0.000 0089 cm. 0.000 0178 cm.
Apparatus c	d = 14.8 inches = 37.6 cm. w = 0.000 0376 cm.	4.25 to 60 inches = 10.8 to 152.4 cm. Contents of cylinder usually dry or nearly so.

DESCRIPTION OF METHOD (A) AND APPARATUS.

The ideal aimed at in the disposition of the apparatus was to obtain a concave surface of polished silver at constant temperature, having the bolometer strips at its center of curvature, and completely filling the circular openings in the multiple bolometer screens of polished metal. Radiations proceeding from the bolometer toward the concave mirror (distant about 125 cm.) would then be directly returned, except as affected by absorption, while rays from any objects in front of the mirror, but outside of the cone of rays from the bolometer to the mirror's edge, could not possibly be reflected upon the bolometer.

The bolometer being at the bottom of the deep cylindrical cavity of its ebonite case,* protected from air currents by internal diaphragms, and further shielded by the multiple metallic screens already mentioned, it was arranged to transpose the volume of air intervening between the mirror and the outer bolometer screen, and to substitute volumes of hot or cold air so rapidly

* See Plate 2, accompanying Prof. S. P. Langley's article "On Hitherto Unrecognized Wave-lengths," in *Am. Journ. of Sci.*, vol. 132.

that the temperature of the bolometer should remain unaffected save by the feeble radiation of the gas, the temperature of the concave mirror being expected to remain appreciably unchanged in the brief interval of exposure, owing to the small absorption of radiation by silver and the continual circulation of water within the metallic walls, as will be now described.

The mirror was made of silver-plated copper, so as to be both a good conductor and a poor radiator, but owing to the thinness of the copper and its yielding quality it was found difficult to preserve the spherical figure. The mirror formed the central portion of the front face of a rectangular vessel containing water at the temperature of the room, and on testing its figure, certain small portions, as viewed from the position of the bolometer, were found to reflect light from a lamp flame placed outside, but close alongside the aperture of the bolometer screen. It was evident, therefore, that some of these distorted surfaces might reflect enough radiation from the interior blackened walls of the cases containing the hot and cold air to entirely vitiate the result.

It was recognized from the start that the radiating power of a gas is so greatly at a disadvantage, compared with the emissive power of a solid, that the least exposure of hot or cold metal in front of the bolometer would give thermal indications, which might very easily be greater than those to be expected from the short air column available for experiment. The failure to obtain a perfect spherical reflector which should also be a good conductor, without going to greater expense than was deemed advisable, led to a partial modification of the original plan in the coating of the mirror with lampblack. The layer of soot being very thin, must retain (it was supposed) substantially the temperature of its metallic backing, in spite of its being a good absorbent of radiation,* while the greater part of the blackened spherical surface remains incapable of reflecting outside rays to the bolometer, owing to its shape, except in a weak, diffusive way, and the specular reflections from the small distorted areas are rendered ineffective owing to the feeble reflecting power of lampblack and the obstruction of rays reflected from silver in traversing the discontinuous particles of powdered carbon.

The first experiments were made to compare results with silver and with lampblack for a background, in order to get a knowledge of the magnitude of the errors which are to be guarded against, and of the legitimate radiations at our disposal.

The movable air chambers were cylindrical vessels of tin plate, 8 inches in diameter, and 36.4 inches long, provided with diaphragms of circular aperture, 6 inches apart, and graduated from an opening of 2 inches at the end next to the bolometer, to one of 7 inches at the further extremity, adjacent to and circumscribing the mirror face. The inner surfaces of the air chambers were blackened, and apertures were provided at the middle, and 8 inches from each end, for the insertion of thermometers, whenever the temperature was read. The bulbs were, of course, drawn outside the limits of the radiating space during actual work. The air cylinders were contained in tanks 3 feet long, and 1 foot square in transverse section, the cylinders projecting slightly at either end, and being unjacketed at these ends, but being otherwise completely surrounded by the contents of the tanks, which contained either hot or cold water, or a freezing mixture. The tanks were mounted on a rolling carriage, moving between guides, and could be drawn to an accurately adjusted stop on one side or the other, so as to bring the longitudinal axis of either air chamber in line with the bolometer and the center of the mirror; and this could be accomplished by the observer at the galvanometer by pulling a cord passing over pulleys to the movable carriage, thus transposing the air vessels, while simultaneously observing and recording the galvanometer readings.

The outermost aperture of the bolometer's multiple metallic screen, 1.15 inches in diameter, at 12.3 inches from the instrument, was concentric with the 2-inch aperture of the near end of the air chamber which was 13.2 inches from the bolometer, and since the angular aperture of the opening in the screen, as seen from the bolometer, namely 5°.35, was much smaller than those of the air chamber, which were 8°.67 for the near aperture, and 8°.07 for the further opening in front of the mirrior, there was no danger that any portion of the walls of the air chamber could be directly observed.

Since in shifting the air chambers to and fro, the larger or 7-inch aperture remained always

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*How far this supposition is invalidated will be shown in the sequel.

nearly in juxtaposition with the silvered face of the fixed water tank, very little air could escape at this end, and that which entered at the 2-inch aperture was prevented from having free circulation by the internal diaphragms. It was found that with an excess of 60° C., the excesses of either of the internal thermometers of the air chamber above the temperature of the outside air seldom differed from the mean by as much as 5 per cent. The temperature gradient of the central axis of the air chamber has therefore usually been quite moderate.

The following temperature readings for a single day, March 15, 1892, are given in proof of this statement:

TABLE 15.

Excess of hot cylinder above outside air temperature as inferred from the mean of the three thermometers.	Mean variation of three internal thermometers.
° C.	° C. Per cent.
67.8	± 0.6 = 0.9
70.1	± 0.8 = 1.1
69.5	± 0.9 = 1.3
66.9	± 1.9 = 2.8
65.0	± 0.4 = 0.6
61.0	± 1.0 = 1.6
65.4	± 2.1 = 3.2
61.8	± 1.8 = 2.9
60.7	± 0.8 = 1.3
56.3	± 1.4 = 2.5

There being no constant order in the relative excesses of the three thermometers, their mean has been adopted as the average temperature of the air column.

CORRECTION FOR THE MAGNETIC EFFECT OF THE APPARATUS DURING MOTION IN METHOD (A).

The positions of stone piers, and other necessities of the case, compelled the placing of the principal apparatus in a position where the shifting of its iron parts feebly, but appreciably, affected the very sensitive galvanometer. Comparisons of the galvanometer readings in extreme positions of the two air cylinders were therefore made, under otherwise identical conditions, to obtain the magnetic effect upon the galvanometer, due to the movement of these considerable masses of tinned iron at an average distance of 12 feet from the magnetic needle.

Experiment of July 29, 1892.

All parts of the apparatus were substantially at the temperature of the room. No conceivable cause, therefore, existed for any temperature deflection. Moreover, variation of the thermal conditions by making the blackened silver screen hot, but leaving the intermediate air cylinders cool and equal in temperature, gave practically the same result, though obviously a less trustworthy one, since it is difficult to maintain the temperature of the hot screen constant.

Exposures were made by alternating west and east cylinders — that is, by bringing the central axis of each cylinder in turn into the line of collimation of the bolometer. To eliminate galvanometer drift, each pair of readings with west cylinder in line was compared with the intermediate reading with east cylinder in line.

	° C.
Temperature of west cylinder (near thermometer),	29.3
Temperature of west cylinder (middle thermometer),	29.3
Temperature of east cylinder (rear thermometer),	29.0
Temperature of east cylinder (middle thermometer),	27.8
Temperature of blackened water-filled screen,	27.8

TABLE 16.

First series.				Second series.			
West cylinder in line.	Mean west.	East cylinder in line.	Deflection east.	West cylinder in line.	Mean west.	East cylinder in line.	Deflection east.
			div.				*div.*
101.2				99.0			
97.3	99.3	102.8	+3.5	95.0	97.0	101.9	+4.9
98.0	97.7	102.0	+4.3	96.9	96.0	100.1	+4.1
98.2	98.1	101.0	+2.9	99.2	98.1	101.8	+3.7
96.1	97.2	101.0	+3.8	97.0	98.1	101.5	+3.4
98.5	97.3	101.0	+3.7	96.6	96.8	102.0	+5.2
97.3	97.9	101.8	+3.9	97.9	97.3	101.3	+4.0
93.9	95.6	99.0	+3.4	96.4	97.2	100.7	+3.5
96.0	95.0	100.2	+5.2	95.9	96.2	100.9	+4.7
98.8	97.4	100.1	+2.7	94.2	95.1	98.5	+3.4
98.8	98.8	101.6	+2.8	93.7	94.0	98.0	+4.0
Mean,			+3.62	Mean,			+4.09

The probable errors of the two series being $\pm$ 0.16 div. and $\pm$ 0.14 div., equal weights may be given to them, and their common mean applied with opposite signs, according as the change of position is from west to east, or the reverse, whence the mean magnetic deflection by presentation of east cylinder = + 3.86 div.; by presentation of west cylinder = − 3.86.

OBSERVATION OF AIR RADIATION BY METHOD (A).

The radiation measures with the first apparatus follow. The sensitiveness of the galvanometer during these experiments remained unchanged. The astaticism, checked from day to day, continued constant. The time of a half vibration of the needle, chronographically determined, was 9.7 seconds.

A comparison of deflections with polished silver and blackened reflector showed that the former were from two to three times the greater, proving, as had been anticipated, that the reflections from the distorted surface of the silver were larger than the air radiation to be measured. It is only necessary, then, to consider those measures in which, the bolometer being directed to the concave blackened surface, the alternate interposition of hot or cold columns of air has given small but consistent positive deflections from the heated air. There remains only the uncertainty whether, in spite of the backing of conducting copper and water, the outer radiant layer of the lampblack may not change temperature by contact with the hot and cold air. This point will be considered in connection with the results of other methods.

Each interposition of hot air has been made between a pair of cold ones whose mean is taken for comparison, and the movements have been regularly timed in such a way as to allow the galvanometer needle just time enough to complete its swing, 11 consecutive readings on the cold air and 10 intermediate ones on the hot air, forming a series, as in the example at constant temperature in Table 16.

Experiments of March 10, 1892.

West cylinder heated.
East cylinder surrounded by refrigerating mixture of snow and salt.

TABLE 17.

	Before first series.	Between series.	After second series.	Mean first series.	Mean second series.	Deflections (hot). First series.	Deflections (hot). Second series.
						div.	*div.*
Temperature of bolometer	15°.0 C.	14°.4 C.	14°.5 C.	14°.7 C.	14°.5 C.	15.0	13.4
" " screen	20°.0 C.	19°.6 C.	19°.2 C.	19°.8 C.	19°.4 C.	17.3	11.2
" " room	12°.3 C.	12°.2 C.	12°.1 C.	12°.3 C.	12°.2 C.	15.2	15.8
Pressure of atmosphere	729.0 mm.	(At 0° C.)		729.0 mm.	729.0 mm.	12.9	15.4
Dew-point	5°.6 C.	5°.6 C.	5°.6 C.			13.1	14.4
Pressure of water vapor				6.78 mm.	6.78 mm.	12.9	15.9
Water per cubic meter				7.03 grams.	7.03 grams.	11.0	16.5
Temperature of hot air	57°.1 C.	54°.2 C.	48°.8 C.	55°.7 C.	51°.5 C.	17.1	15.6
" " cold "	—12°.2 C.	—11°.3 C.	— 9°.5 C.	—11°.8 C.	—10°.4 C.	11.2	15.4
" excess	69°.3 C.	65°.5 C.	58°.3 C.	67°.5 C.	61°.9 C.	13.4	13.1
Mean deflections						13.91	14.67

The probable error of the mean of the first series is ± 0.51 div., and of the second, ± 0.37 div. The battery galvanometer stood at 99 div., and the deflections, reduced to the standard current (100 div.) and corrected for the negative magnetic deflection of the west cylinder, become—

$$\text{First series:}\quad (+\ 13.91 + 3.86) \div 0.99 = +\ 17.95 \text{ div.}$$

$$\text{Second series:}\quad (+\ 14.67 + 3.86) \div 0.99 = +\ 18.72 \text{ “}$$

The mean temperature of the hot-air column was 39°.0 above that of the bolometer, and the cold air was 25°.7 below the instrument. The mean atmospheric pressure was 729 mm. and the force of water vapor 6.78 mm., equivalent to a layer of liquid water 0.000 236 cm. thick in the absorbent column, 33.5 cm. long.

Experiments of March 15, 1892.

West cylinder heated.
East cylinder surrounded by cool water of nearly the same temperature as the bolometer. Silvered reflector freshly blackened by smoking it over a smoky lamp flame.

TABLE 18.

	Before first series.	Between series.	After second series.	Mean first series.	Mean second series.	Deflections (hot). First series.	Deflections (hot). Second series.
						div.	*div.*
Temperature of bolometer			8°.7 C.	8°.7 C.	8°.7 C.	16.1	13.6
" " screen		7°.9 C.	8°.0 C.	8°.0 C.	8°.0 C.	15.0	12.7
" " room	4°.4 C.	5°.2 C.	3°.1 C.	4°.8 C.	4°.2 C.	18.2	19.0
Pressure of atmosphere	738.4 mm.	(At 0° C.)		738.4 mm.	738.4 mm.	14.2	13.8
Dew-point	—10°.0 C.	— 8°.9 C.	— 7°.8 C.			14.2	7.7
Pressure of water vapor				2.35 mm.	2.55 mm.	15.7	12.9
Water per cubic meter				2.57 grams.	2.78 grams.	10.2	13.4
Temperature of hot air	73°.9 C.	72°.1 C.	68°.1 C.	73°.0 C.	70°.1 C.	10.2	12.9
" " cold "	+ 7°.9 C.	+ 7°.5 C.	+ 6°.8 C.	+ 7°.7 C.	+ 7°.2 C.	12.1	15.4
" excess	66°.0 C.	64°.6 C.	61°.3 C.	65°.3 C.	62°.9 C.	17.5	18.2
Mean deflections						14.34	13.96

The probable errors of the mean deflections are ± 0.61 div. and ± 0.60 div. Battery galvanometer = 102 div. Deflections reduced to standard and corrected:

First series: (+ 14.34 + 3.86) ÷ 1.02 = + 17.84 div.

Second series: (+ 13.96 + 3.86) ÷ 1.02 = + 17.47 "

The mean atmospheric pressure was 738.4 mm., and the mean force of water vapor 2.45 mm., equivalent to a liquid layer 0.000 090 cm. thick in the length of the absorbent column of air.

In the third and fourth series, the tank around the cold cylinder was filled with a mixture of snow and salt, giving as wide a range of temperature as the structure of the apparatus would permit.

TABLE 19.

	Before third series.	Between series.	After fourth series.	Mean third series.	Mean fourth series.	Deflections (hot).	
						Third series.	Fourth series.
						div.	*div.*
Temperature of bolometer	8°.7 C.		9°.3 C.	8°.9 C.	9°.2 C.	18.0	18.2
" " screen	8°.0 C.		8°.0 C.	8°.0 C.	8°.0 C.	15.2	17.8
" " room	4°.2 C.	5°.6 C.	6°.3 C.	4°.9 C.	6°.0 C.	21.3	20.9
Pressure of atmosphere	(Approximately.)			738 mm.		16.3	21.3
Dew-point	—3°.3 C.	—3°.1 C.	—1°.1 C.			18.6	17.7
Pressure of water vapor	3.59 mm.	3.64 mm.	4.22 mm.	3.62 mm.	3.93 mm.	24.0	17.3
Water per cubic meter	3.84 grams.	3.90 grams.	4.48 grams.	3.87 grams.	4.19 grams.	21.5	21.9
Temperature of hot air	69°.6 C.	67°.4 C.	67°.0 C.	68°.5 C.	67°.2 C.	18.4	23.2
" " cold "	—15°.2 C.	—15°.0 C.	—14°.4 C.	—15°.1 C.	—14°.7 C.	16.9	18.8
" excess	84°.8 C.	82°.4 C.	81°.4 C.	83°.6 C.	81°.9 C.	19.9	18.6
Mean deflections						19.01	19.57

The probable errors are ± 0.60 div. for the third, and ± 0.51 div. for the fourth series, and the corrected deflections are—

Third series: (+ 19.01 + 3.86) ÷ 1.02 = + 22.42 div.

Fourth series: (+ 19.57 + 3.86) ÷ 1.02 = + 22.97 "

The mean air pressure was about 738 mm., and the mean force of vapor 3.78 mm., equivalent to a liquid layer of water 0.000 135 cm. deep in a length of 33.5 cm.

Experiments of July 29, 1892.

Object: The measurement of radiation from warm air, containing considerable water vapor, for comparison with results obtained in cold, dry weather. Also a determination of the absorption of this radiation by glass.

East cylinder the hot one, the magnetic influence of moving masses being therefore the reverse of that in previous measures. West cylinder surrounded by melting ice. Silvered reflector, forming the background, freshly coated with soot.

The first and fourth series are comparable with previous measures, varying only in the higher range of temperature and the larger quantity of water. In the second and third series, the aperture of the bolometer case was covered by a pane of window glass 3.15 mm. thick, which transmits about 76 per cent. of the total apparent solar radiation, and 14 per cent. of that from the moon, and which is practically impervious to rays of greater wave-length than 4½ microns, giving us, in the absence of spectrobolometric measures, a preliminary approximation to the region of the spectrum in which the radiation lies.

TABLE 20.

	Before first series.	After second series.	After fourth series.	Adopted for 1 and 2.	Adopted for 3 and 4.
Temperature of bolometer	32°. 0 C.			32°. 0 C.	32°. 0 C.
" " screen	29°. 7 C.	29°. 8 C.	30°. 0 C.	29°. 8 C.	29°. 9 C.
" " room	32°. 6 C.		32°. 0 C.	32°. 5 C.	32°. 2 C.
Pressure of atmosphere	730. 74 mm.	(At 0° C.)	731. 76 mm.	731. 0 mm.	731. 5 mm.
Dew-point	23°. 9 C.		23°. 3 C.		
Pressure of water vapor				21. 63 mm.	21. 63 mm.
Water per cubic meter				21. 06 grams.	21. 06 grams.
Temperature of hot air	93°. 2 C.	89°. 1 C.	89°. 5 C.	91°. 2 C.	89°. 3 C.
" " cold "	+6°. 5 C.	+8°. 2 C.	+8°. 2 C.	+7°. 4 C.	+10°. 6 C.
" excess	86°. 7 C.	80°. 9 C.	80°. 9 C.	76°. 5 C.	78°. 7 C.

DEFLECTIONS FROM HOT-AIR COLUMN.*

	First series.	Second series.	Third series.	Fourth series.
	div.	*div.*	*div.*	*div.*
	21. 1	10. 1	3. 8	26. 9
	18. 5	3. 4	2. 8	27. 8
	25. 0	7. 4	4. 5	22. 5
	23. 6	5. 9	5. 3	20. 6
	24. 8	4. 1	6. 4	24. 4
	26. 3	9. 1	4. 7	21. 9
	29. 0	4. 3	6. 0	22. 5
	24. 0	4. 5	6. 2	21. 7
	24. 0	4. 5	6. 4	24. 6
	29. 3	2. 6	7. 0	24. 4
Mean deflections	24. 56	5. 59	5. 31	23. 73

* Series 1 and 4 without glass, 2 and 3 through glass.

The probable errors of the means, in the order of the series, are ± 0.65 div., ± 0.57 div., ± 0.31 div., ± 0.53 div.; and the battery galvanometer reading being 96.5 div., the deflection , corrected for the positive magnetic deflection of the east cylinder, and reduced to the standard current, are—

First series: $(+ 24.56 - 3.86) \div 0.965 = + 21.45$ div.
Second series: $(+ 5.59 - 3.86) \div 0.965 = + 1.79$ "
Third series: $(+ 5.31 - 3.86) \div 0.965 = + 1.50$ "
Fourth series: $(+ 23.73 - 3.86) \div 0.965 = + 20.59$ "

The glass used transmits

	μ
31 per cent. of radiation of wave-length,	1.9
18 " " " " " " "	3.1
8 " " " " " " "	4.3

Not over $\frac{1}{20}$ of the radiation from a surface of lampblack, at the temperatures with which we are dealing, lies in this region of very limited glass transmission. Most of the fraction, indeed, will be near the longest wave-length mentioned, and 0.1 is a fair index of its average transmission by glass, so that, if we say that it is hardly possible for $\frac{1}{200}$ of the rays from the lampblack background to escape absorption by glass, the statement is justifiable. If the deflection of about $1\frac{1}{2}$ div. through glass is genuine, it must be of atmospheric origin. As the absorption of glass is a discontinuous one, at any rate in this part of the spectrum, it is possible that the absorption of a linear gaseous spectrum whose lines or bands do not coincide with those of glass, may be much less than for a continuous spectrum like that of lampblack, and that 8 per cent. transmitted in the present case may represent a fraction of gaseous radiation either of shorter wave-length than $4\frac{1}{2}$ microns, or of greater wave-length than the region of lampblack emission, comparatively unabsorbed.

In proof of the statement that the absorption of glass is discontinuous, it may be mentioned

that rays in a small part of the lampblack spectrum from a glass prism, in the region near 2μ, were found to be three times as transmissible by glass as in the same region from a rock-salt prism, showing that certain rays which are present in the rock-salt prismatic spectrum, have been entirely cut off in the spectrum from the glass prism, and that those rays which remain pass through glass with comparative freedom.

The mean atmospheric pressure in the experiments of July 29, was 731.3 mm., the vapor pressure 21.63 mm., and the equivalent layer of liquid water in the absorbent air column was 0.000 706 cm., that in the radiant hot-air column being about twice as great, and five to seven times as great as in the experiments of March 15. If the greater amount of water in the summer air has increased its radiative power, the deflections in series 1 and 4, July 29, ought to exceed those in series 3 and 4, March 15; indeed, without any change in radiant emissivity, some increase of radiation was to be anticipated, because, although the temperature-excesses were smaller in July, the range was on a part of the temperature scale farther from absolute zero, and where the differential radiation, as shown in the figures for lampblack (Table 21), may be expected to be greater. The summer deflections are actually a little smaller, indicating that the radiation measured has been, to a considerable extent, that of the lampblack background, which has suffered greater absorption by water in summer. The following tables exhibit these relations, the last columns being stated in absolute radiant units. The radiating volume of air has the form of a truncated cone whose angle is 5°.35, the length of the frustum and depth of the radiating layer being 92.5 cm., the diameter of its smallest section 3.1 cm., and that of its largest and most distant section 11.8 cm., while the volume of the frustum is 4,510 cub. cm. The measured radiation approaches the half of what might be expected from surfaces of lampblack at the given temperatures.

TABLE 21.

Date and series.	Temperatures. Cent. t	Temperatures. Absol. T	Computed lampblack radiation to a hemisphere.	Ratio to lampblack radiation from 100° to 0° C. r	Computed lampblack radiation through small aperture. $E_2 \times r$
	°	°	*Radim.*		*Radim.*
March 10, 1892 (1)	56 —12	329 261	.0135 } .0070 .0065 }	$\frac{70}{126}$ = .556	0.000 001 355
" (2)	52 —10	325 263	.0129 } .0063 .0066 }	$\frac{63}{126}$ = .500	0.000 001 214
March 15, 1892 (1)	73 8	346 281	.0158 } .0076 .0082 }	$\frac{76}{126}$ = .603	0.000 001 469
" (2)	70 7	343 280	.0155 } .0075 .0080 }	$\frac{75}{126}$ = .595	0.000 001 450
" (3)	69 —15	342 258	.0153 } .0090 .0063 }	$\frac{90}{126}$ = .714	0.000 001 740
" (4)	67 —15	340 258	.0150 } .0087 .0063 }	$\frac{87}{126}$ = .690	0.000 001 682
July 29, 1892 (1)	91 7	364 280	.0186 } .0106 .0080 }	$\frac{106}{126}$ = .841	0.000 002 050
" (4)	89 11	362 284	.0184 } .0100 .0084 }	$\frac{100}{126}$ = .794	0.000 001 935

For the equivalent water depths in the first three columns of the next table, reductions of water vapor in terms of mass (m), stated in grams per cubic meter, have first been made from the indicated vapor pressures (p) and barometric pressures (B), reduced to the freezing point, using the formula—

$$m = 1\ 000\ 000 \times \frac{p}{B} \times \frac{0.000\ 8041}{1 + 0.003\ 670t}$$

where t is the centigrade temperature of the hot or cold air in the radiant air column. These masses have then been multiplied by the factor (w) in Table 14. The liquid depths are given in millionths of a centimeter.

TABLE 22.

Date and series.	Liquid water in— Radiant layer. Hot.	Cold.	Absorbent layer.	Corrected deflection. δ	Temperature excess.	Measured radiation.
				Divisions.	° C.	*Radim.*
March 10, 1892 (1)	567	200	236	17.95	67.5	0.000 000 740
" (2)	574	223	236	18.72	61.9	0.000 000 771
March 15, 1892 (1)	186	230	93	17.84	65.3	0.000 000 735
" (2)	204	250	93	17.47	62.9	0.000 000 720
" (3)	291	153	130	22.42	83.6	0.000 000 924
" (4)	317	158	140	22.97	81.9	0.000 000 946
July 29, 1892 (1)	1473	754	706	21.45	76.5	0.000 000 884
" (4)	1480	916	706	20.59	78.7	0.000 000 848

EXAMINATION OF PROFESSOR HUTCHINS' HYPOTHESIS "THAT RADIATION TAKES PLACE ONLY WHEN THERE IS A FALL OF TEMPERATURE WITHIN THE LIMITS OF MOLECULAR ACTION."

In a research on the Radiation of Atmospheric Air (*Am. Journ. of Sci.*, vol. 43, p. 357–363, May, 1892) Prof. C. C. Hutchins endeavors to determine the effect of varying the thickness of a radiating layer of air. "A flat sheet-iron pipe was made 100 cm. long, 10 cm. wide, and 2.5 cm. thick." This pipe was supported in an inclined position and heated by Bunsen burners. "The air exit was from a pair of jaws, one fixed, one movable, so that the thickness of the air column at its escape could be regulated at pleasure. * * * The results were recorded as the amount of galvanometer deflection per degree of $t - t'$. With openings less than 1 cm. no difference in the amount of radiation can be detected. With larger openings a small increase is observed."

	cm.	cm.	cm.	cm.
Opening,	0.5	1	2	3
Deflection per degree,	0.193	0.195	0.245	0.259

The conclusion drawn is "that radiation is very largely from the surface of contact between the hot and cold air, which seems to indicate that a heated gas absorbs all or nearly all those rays that it itself emits, and that radiation takes place only when there is a fall of temperature within the limits of molecular action" (p. 363, *loc. cit.*). The values given show that when the air aperture was enlarged sixfold, radiation only increased in the ratio of 259 to 193, or by 34 per cent.; but it seems to me that the inferences are not warranted. The uprushing jet draws cool air from the sides and mingles it with the hot air, and the effect of this admixture is proportionally greater in a narrow jet, so that until the aperture is considerably greater than those used by Professor Hutchins, the cooling by admixture very nearly neutralizes any gain from greater depth in the line of sight. The viscosity of air prevents an indefinite extension of the mixing. A jet of more than a certain depth at a given altitude above the nozzle will have its temperature lowered by mixture only at the borders of the ascending air column, the central part of the cross section of the heated air having a constant temperature. Except for absorption of its own radiation by the air any further increase of depth will then give radiant values greater in approximate proportionality to the thickness of the layer. Professor Hutchins appears to have been deceived by an eye observation, which he describes on page 359 (*loc. cit.*). "By burning touch paper at the bottom of the tube, the lamps beneath being lighted, the shape of the column of air from the nozzle can be inspected at leisure by reason of the dense smoke that issues with it, and by filling the throat of the nozzle it can be given such a shape that the column of heated air will preserve uniform dimensions for a considerable distance from its exit." On the strength of this observation of a uniformity of cross section in the ascending air column, a constant velocity and identical composition of the jet "for a considerable distance from its exit" seems to have been

inferred; but this is incorrect, since, as I shall show, the thermal gradient of a cross section of the air column is not only not a single valued quantity in a given instance, but the form of the gradient varies with the aperture of the nozzle, and this implies variation of velocity and more or less admixture of cool air.

DESCRIPTION OF METHOD B.

Method A having been discredited, or at least having come under suspicion, no attempt was made to extend it to air columns of other dimensions; but, instead, the bolometer was pointed to a cold screen entirely separated from the hot air which issued from an effluent chamber of wood (fig. 3) placed over the hot-air flue from the furnace, whose register could be opened or closed by pulling cords.

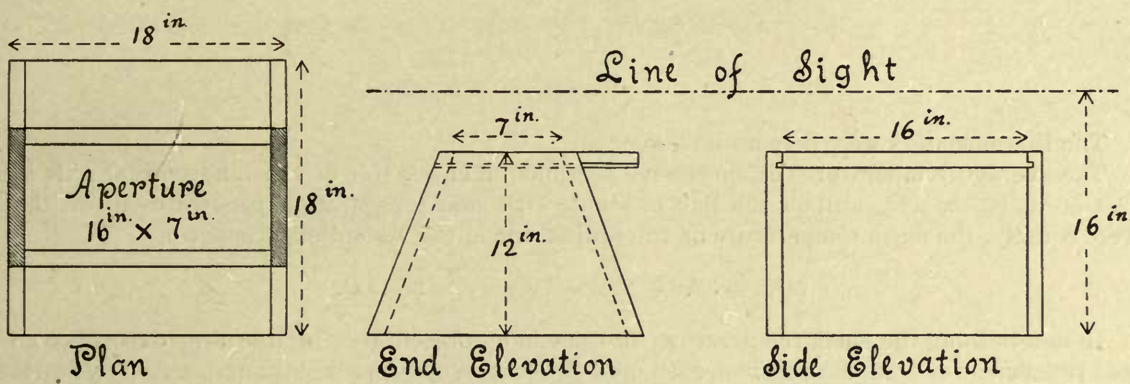

Fig. 3

The aperture through which the hot air issues has a length of 16 inches (40.6 cm.) and a breadth of anything less than 7 inches (17.8 cm.), as determined by the position of a sliding panel. By rotating the wooden casing through 90°, either the longitudinal or the transverse axis of the aperture can be made parallel to the line of sight, giving different depths of radiating air without altering the section and general condition of the air stream. By means of the sliding panel both the depth and sectional area of the air stream may be varied.

The hot air within the wooden effluent chamber does not entirely escape upon shutting the register. The temperature within the aperture was 17°.6 higher than that of the air in the line of sight, 4 inches (10.2 cm.) above the aperture, when the register was closed; but with the register open, the strong current of hot air maintained a uniform temperature in the vertical direction, although there was a considerable thermal gradient in the horizontal direction along the transverse axis.

Experiments of February 23, 1893.

The bolometer was placed 18 inches (45.7 cm.) from a vertical line through the center of the aperture. When the aperture (16 by 6 inches) was end-on, the cone of rays included the diameter of the air vein in the most distant section. The temperature of the air around the bolometer strips, as determined by a thermometer bulb inside the bolometer case, was 10°.8 C. at the beginning, and 9°.8 at the close. Successive readings of the temperature of the air of the room at intervals of some minutes were 4°.3, 4°.5, 5°.0, 4°.3, 4°.5. The temperatures on which the deflections depend are those of the air in the line of sight. Three thermometers were placed in the longitudinal axis of the aperture: (*a*) 3 inches from its farther end and 5 inches from the center, (*b*) at the center, and (*c*) 3 inches from the nearer end. The temperature within the

aperture (register shut) was 24°.0. The thermometers, elevated into the line of sight, had a mean temperature of 6°.4 which is that of the cold air.

In the hot air, the readings were—

	First Series.			Second Series.		
	°		°	°		°
(a)	55.8	Excess,	49.4	57.0	Excess,	50.6
(b)	56.2		49.8	59.2		52.8
(c)	56.0		49.6	50.5		44.1
		Mean excess,	49.6		Mean excess,	49.2

The thermal gradient of the transverse diameter of the air vein is represented, on the average, by the following series:

49°

46° 46°

30° 30°

15° 15°

0 Excesses. 0

The thermometers were here an inch apart.

The average temperatures of successive sections on either side of the longitudinal axis are: 47°.5, 38°.0, 22°.5, 7.°5; and as the line of sight, with side presentation, penetrates all of these layers equally, the mean temperature of the radiant air in the second experiment is

$$(47.5 + 38.0 + 22.5 + 7.5) \div 4 = 28^\circ.9 \text{ C.}$$

In determining the mean temperature for the end-on presentation of the first experiment, no great refinement of computation is needed, and the section may be roughly summarized by fourths, as indicated in fig. 4.

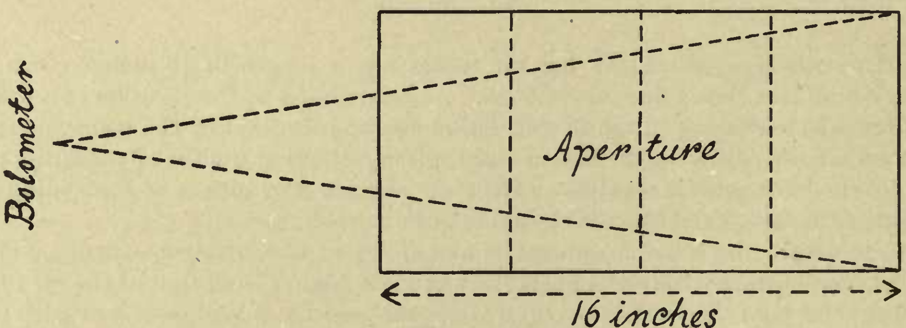

Fig. 4 (Plan)

In end-on presentation it is to be noted that, although the aperture has a width of 6 inches, the heated air spreads to a width of about 8 inches at the level of the line of sight, and the bolometer with its widest angular opening takes in the whole of this width at the distance of the farther end of the aperture, as shown in the diagram.

The most distant quarter of the air vein may be divided into eight vertical layers, 1 inch thick, and having the average temperatures just given. Cutting these layers by a horizontal cylinder which includes the extreme width, the areas of the successive transverse sections, counting from the axial ones, are:

(1)	$1.571-1.076=0.495$
(2)	$1.076-0.614=0.462$
(3)	$0.614-0.227=0.387$
(4)	0.227
	Sum$=\frac{1}{2}\pi=1.571$

To obtain the mean temperature of the entire section, these areas may be treated as weights, giving as the temperature of the most distant fourth of the air vein—

$$t_4 = \frac{47.5 \times .495 + 38.0 \times .462 + 22.5 \times .387 + 7.5 \times .227}{1.571}$$
$$= 32^{\circ}.8 \ C.$$

Similarly, the next nearer quarter of the air vein may be considered as composed of six vertical layers of the central hotter region cut by an including cylinder, the areas of successive sections being—

(1) $1.571 - 0.916 = 0.655$
(2) $0.916 - 0.343 = 0.573$
(3) 0.343

The mean temperature of the next to the most distant fourth is then—

$$t_3 = \frac{47.5 \times .655 + 38.0 \times .573 + 22.5 \times .343}{1.571}$$
$$= 38^{\circ}.6 \ C.$$

The nearer half of the air vein may be assumed to consist of the four inner vertical layers and the areas of their sections—

(1) $1.571 - 0.614 = 0.957$
(2) 0.614

The mean temperature of the first and second fourths of the air vein is:

$$\frac{t_1 + t_2}{2} = \frac{47.5 \times .957 + 38.0 \times .614}{1.571}$$
$$= 43^{\circ}.8 \ C.$$

The final mean is, for first experiment—

$$(32.8 + 38.6 + 43.8 + 43.8) \div 4 = 39^{\circ}.7 \ C.$$

The observed galvanometer deflections were as follows:

TABLE 23.

First series (aperture end-on).	Second series (aperture sidewise).
div.	*div.*
11.8	4.0
9.9	1.7
12.2	3.1
6.9	2.9
6.3	0.0
11.8	3.8
14.5	2.3
12.2	1.5
9.2	4.2
8.0	5.3
Mean $= 10.28 \pm 0.62$	Mean $= 2.88 \pm 0.34$

Multiplying the mean temperatures by the depths of the radiating air layers, assuming these

to be proportional to the dimensions of the aperture in the direction of the line of sight, the computed air radiations and their ratio are—

$$\begin{array}{ll} (1) & 16 \times 39.7 = 635.2 \\ (2) & 6 \times 28.9 = 173.4 \end{array} \Bigg\} \cdots\cdots \frac{173.4}{635.2} = 0.273$$

The observed ratio is—

$$2.88 \div 10.28 = 0.280$$

the radiation for the greater depth being only a trifle less than its proportion according to the product of depth and temperature.

The battery galvanometer read 96 div. Reduced to standard current and stated in absolute units the radiations become—

(Depth, 40.6 cm.)	Radiation	= 10.71 div.	= 0.000 000 545	radim.
(" 15.2 cm.)	"	= 3.00 div.	= 0.000 000 153	"

For comparison with the results of the previous method, these deflections have to be reduced to the smaller aperture by dividing by 8.96, giving—

(Depth, 40.6 cm.)	Radiation	= 1.20 div.	= 0.000 000 049	radim.
(" 15.2 cm.)	"	= 0.33 div.	= 0.000 000 014	"

With a depth of 92.5 cm. and an excess of 65°, assuming proportionality of radiation to depth and temperature combined, an assumption which now seems justifiable in this first approximation, we might anticipate a radiation of—

$$0.000\ 000\ 049 \times \frac{92.5}{40.6} \times \frac{65}{40} = 0.000\ 000\ 181 \text{ radim.}$$

The measured radiation by Method A (Table 22) being about four times as great as this, we must conclude that something like three parts of the observed radiation in Method A were due to an excessively thin layer of warm radiating lampblack, with a small amount diffusively reflected by lampblack, and only one part to the hotter air.

The condition of the air in the experiments of this date was: Barometer, 724 mm.; dew-point, $-5^\circ.3$ C., corresponding to a vapor pressure of 3.09 mm., or to 3.34 grams of water per cubic meter. By Table 14 this represents the following depths of liquid water in the end-on presentation b_1 and the sidewise presentation b_2—

		cm.	
b_1, absorbent layer		= 0.000 085	
radiant	"	= 0.000 135	(cold)
"	"	= 0.000 118	(hot)
b_2, absorbent layer		= 0.000 127	
radiant	"	= 0.000 051	(cold)
"	"	= 0.000 046	(hot)

Experiments of February 25, 1893.

The bolometer was placed 15 inches (38.1 cm.) from a vertical line through the center of the aperture whose width was increased to 7 inches (17.8 cm.), giving a hot-air column a little over 9 inches wide at the level of the line of sight.

The longitudinal axis of the aperture in the end-on position lying east and west, thermometers were placed at the level of the line of sight—

(*a*) in the longitudinal axis of the air column 8 inches E. of center.
(*b*) " " " " " " " 6 " " " "
(*c*) " " " " " " " 3 " " " "
(*d*) " " " " " " " at the center.
(*e*) $2\frac{1}{2}$ inches north of longitudinal, 1 inch east of transverse axis.

To test the effect of the hot air remaining in the effluent chamber after the register was closed, the thermometers were read with the aperture alternately open and closed by a board cover.

	Aperture open.	Aperture closed.
	°	°
(*b*)	8.0	6.3
(*c*)	9.1	7.8
(*d*)	8.6	7.0
(*e*)	6.9	7.2

I have adopted for the temperature of the cold air (register closed, but aperture open)—

$$\frac{\frac{1}{3}(b+c+d)+e}{2} = 7^\circ.7\ C.$$

The temperature of the bolometer case was $10^\circ.8$, and the mean temperature of the air of the room was $6^\circ.0$.

The thermometer readings in the hot-air column in the first series were:

	°	
(*a*)	62.8	
(*b*)	62.8	$66^\circ.4$ = mean of temperatures at east end of longitudinal axis.
(*c*)	68.8	
(*d*)	71.9	
(*e*)	44.2	

In the next series, thermometer (*e*) was transferred to a point in the longitudinal axis, 8 inches west of center—

		°	
East	(*a*)	45.0	
	(*b*)	73.4	
	(*c*)	74.2	Mean of temperatures in longitudinal axis = $66^\circ.8$.
Center	(*d*)	74.8	
West	(*e*)	66.6	

Thermometers (*a*) and (*e*) in this series, being near the point where the thermal gradient becomes very steep, are liable to vary considerably for a slight displacement of the vertical axis of the ascending air column.

The last two series of temperature readings have been taken with thermometers in the transverse axis of the hot-air column in positions at even inches from the center—

	Third series.	Fourth series.
	°	°
3 inches north of center	27.4	32.0
2 " " " "	....	63.0
1 inch " " "	....	70.2
Center	70.2	70.5
1 inch south of center	67.7	68.1
2 inches " " "	63.0	....
3 " " " "	47.8	....
4 " " " "	23.8	....
5 " " " "	....	13.4

These thermal sections show a spreading of the hot air, and its mixture with the surrounding cold air for an inch or so outside the original dimensions of the stream at the aperture of the effluent chamber. The heat, however, is nearly uniform for about 12 inches in the center of the longitudinal axis. Fig. 5 exhibits these thermal gradients to the eye—

Abscissæ = distances from center of air stream.
Ordinates = temperature-excesses (C.).
1 and 2 = series along longitudinal axis.
3 and 4 = " " transverse "

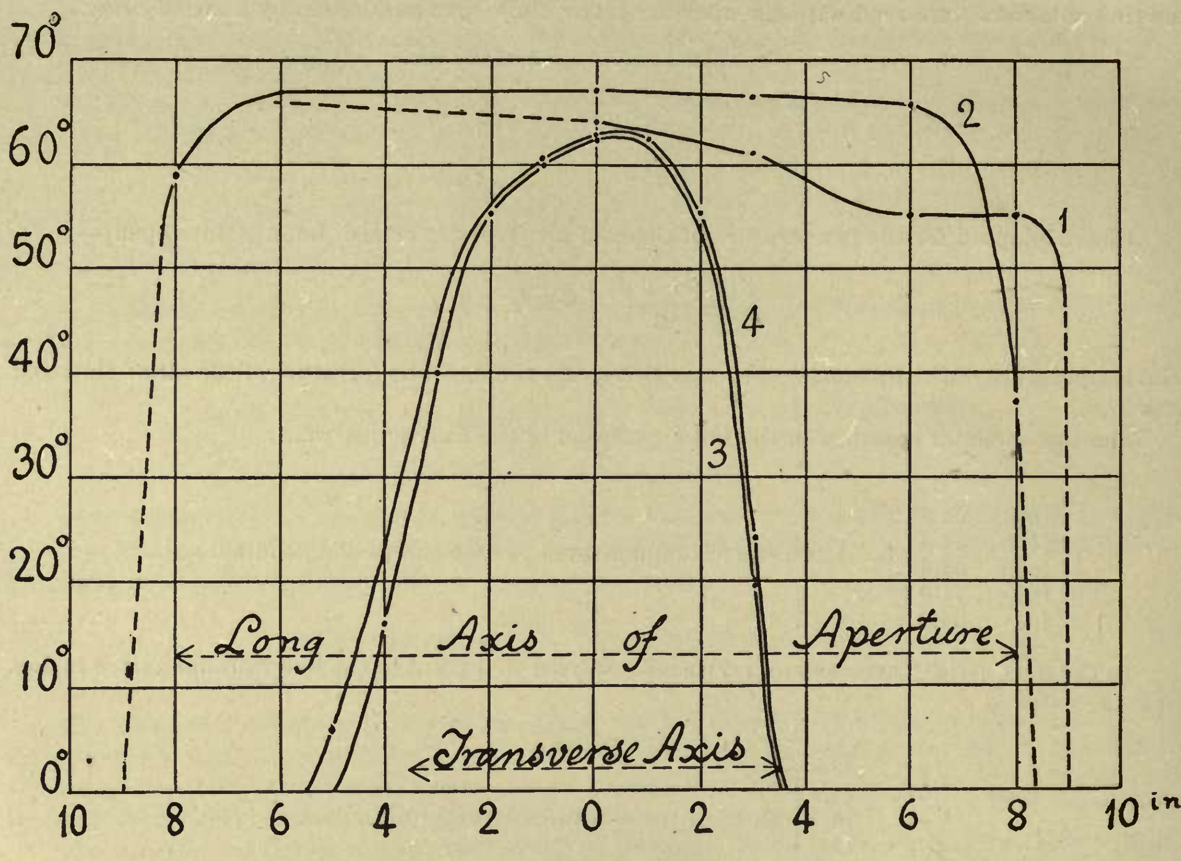

Fig. 5

The average thermal gradient of the transverse axis of the hot-air column may be represented by the following series:

63°
61° 61°
55° 55°
30° 30°
10° 10°
0 Excesses. 0

The average temperatures of successive sections on either side of the longitudinal axis are, 62°, 58°, 42°.5, 20°, 5°; and the mean temperature of the radiant air, when the line of sight agrees with the transverse axis of the air column, is—

$$(62 + 58 + 42.5 + 20 + 5) \div 5 = 37°.5\ C.$$

Fig. 6 shows the disposition of bolometer, aperture, and air stream in the end-on presentation.

In getting the mean temperature for this position, a small allowance has been made for the lack of symmetry of the air column. Dividing the air stream into a nearer and a more distant half, the mean temperature of the former may be taken as 61°. The more distant half varying from a

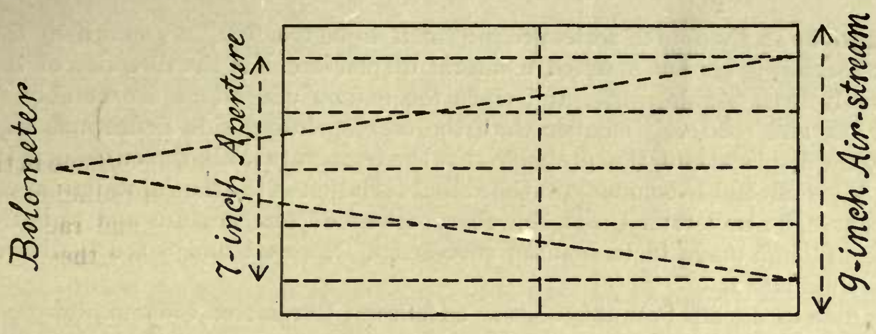

Fig. 6 (Plan)

mean of 61° at the nearest section to 46° at the most distant section, a rough approximation gives its mean temperature, in the part cut off by the cone of rays, as 55°, the final mean for the hot air radiating to the bolometer being 58° C.

Two widths of aperture, 7 and 3½ inches, were used with side presentation. In the end-on position the breadth of the aperture was constantly 7 inches and the length 16 inches. The observed galvanometer deflections follow:

TABLE 24.

First series, end on (16 inches).	Second series, side (7 inches).	Third series, end on (16 inches).	Fourth series, side (3½ inches).
div.	*div.*	*div.*	*div.*
5.2	4.2	7.6	1.7
9.7	4.6	9.7	—1.9
12.8	3.8	12.2	0.8
9.4	3.2	8.4	1.9
11.7	2.3	9.9	0.0
7.6	2.9	12.0	1.0
6.7	2.5	6.5	0.6
9.2	4.6	13.0	0.6
6.5	3.8	4.8	2.7
11.3	2.7	10.1	1.5
9.01±.56	3.46±.21	9.42±.59	0.89±.25

Observed radiation ratios.

Depth, 16 inches (40.6 cm.)	Deflection, 9.22	Ratio, 1.000
" 7 inches (17.8 cm.)	" 3.46	" 0.375
" 3.5 inches (8.9 cm.)	" 0.89	" 0.097

Assuming the radiant depths to be proportional to the dimensions of the aperture parallel with the line of sight and the radiations to be proportional to these depths, computation makes the air radiations and their ratios—

(1) and (3)	$16 \times 58 = 928$	Ratio = 1.000
(2)	$7 \times 37.5 = 262.5$	" = 0.283
(4)	$3.5 \times 37.5 = 131.3$	" = 0.142

The battery galvanometer standing at 99 div., the reduction to standard current and absolute units gives—

Depth 40.6 cm.	Radiation = 9.31 div. = 0.000 000 474 radim	
" 17.8 cm.	" = 3.49 div. = 0.000 000 178 "	
" 8.9 cm.	" = 0.90 div. = 0.000 000 046 "	

The deflections in the fourth series are too small to be trusted. As shown by the transverse gradient, the ascending air has suffered a lateral displacement in the direction of the transverse axis, presumably from a side draft; and since the end-on deflections are notably smaller than on February 23, and relatively smaller than the corresponding side deflections which are not influenced by the displacement, it is probable that the temperature allowance made in the preceding computation is insufficient to compensate the actual variation at the time of radiation measurement. It will, of course, be understood that the observations of temperature and radiation were not synchronous, although made in immediate succession. Series 1 and 3 are therefore given half weight in the final mean.

The condition of the air, February 25, was as follows: Barometer, 726 mm., dew-point, —1.9° C., corresponding to a vapor pressure of 3.98 mm., or to 4.24 grams of water per cubic meter. By Table 14, the depths of liquid water in the various air layers are—

	cm.		cm.	
Radiant depth	40.6	Absorbent layer	= 0.000 075	
		Radiant "	= 0.000 172	(cold)
		" "	= 0.000 142	(hot)
"	17.8	Absorbent "	= 0.000 124	
		Radiant "	= 0.000 075	(cold)
		" "	= 0.000 066	(hot)

TABLE 25.

Radiation of hot air (for small aperture) reduced to a depth of 1 meter.		
		Radim.
Feb. 23	(1)	0.000 000 049 ÷ .406 = 0.000 000 121, t = 40
	(2)	0.000 000 014 ÷ .152 = 0.000 000 092, t = 29
Feb. 25	(1, 3)	0.000 000 043 ÷ .406 = 0.000 000 106, t = 58
	(2)	0.000 000 016 ÷ .178 = 0.000 000 090, t = 38
Radiation of air at mean temperature-excess of 40° C. (Depth 1 meter.)		
		0.000 000 121
		0.000 000 127
		0.000 000 073
		0.000 000 095
		Mean = 0.000 000 104 radim.

DESCRIPTION OF APPARATUS AND METHOD C.

In order to experiment on the radiation of air at various pressures, and to be able also to substitute other gases in the place of air, a closed vessel was needed. Of course this presupposes some sort of window transparent to the gaseous radiation, but both the window pane and the walls of the vessel visible through the window will contribute their own rays, and these must be capable of being certainly distinguished from those of the gas. This was effected by making the window pane of rock-salt and letting the opposite radiant wall be a movable one, formed of a blackened copper disk attached to a steel rod sliding in a stuffing box at one end of a large iron cylinder. By pushing the rod in and out, the length of the radiant air column could be changed without varying the temperature and radiant power of the solid parts. The disk served the further purpose of a stirrer, by the vigorous motion of which it was hoped that the temperature of the hot

air could be made appreciably uniform. This hope was only partially realized, as the sequel will show; but, although it would be possible to devise a more efficient apparatus, the very errors of this one have proved instructive, and the final results, after the discussion and elimination of these errors, are believed to be trustworthy.

The radiation cylinder, as actually made, consists of an iron cylinder of 12 inches internal diameter, 60 inches long, weighing 250 pounds, with flanges at the ends projecting outward to a width of 2 inches. Heavy plates of cast iron are bolted to the flanges, the joints being luted with red rubber. The front end-plate, facing the bolometer, carries lugs and a ring-piece, with clamping screws by which a rubber-faced metal ring is held against a thick plate of rock-salt (thickness, 1.98 inches = 5.03 cm.; diameter, 3.80 inches = 9.65 cm.), holding it against a rubber ring surrounding the 2-inch aperture in the center of the end-plate. A glass plate slides over the outside of the salt, when not in use, to protect it from moisture. Preliminary experiments having proved that rock-salt might be heated to 175° C. and presumably much higher without danger of cracking, if it were shielded from currents of cold air and any sudden changes of temperature, but that without this precaution the salt was almost sure to crack, the circumference of the cylindrical block of salt was wrapped in about an inch of cotton wool. The large masses of metal (the end plates weigh about 20 pounds apiece) prevent any sudden cooling of the solid parts. The rear end-plate being pierced by a central aperture carries a stuffing box through which a half-inch rod of polished steel passes, air-tight, with rubber packing, its position and that of its terminal disk being read by divisions cut on the rod. The movable disk of blackened copper is 0.12 inch thick and 11.85 inches in diameter, leaving an annular opening with an average width of 0.075 inch through which the air rushes when the disk plays to and fro. A thermometer in the front part of the cylinder records the temperature of the air, and the disk is prevented from coming nearer than 4.25 inches (10.8 cm.) to the front plate by a fixed stop. This defines the shortest radiant air column which can be used, the longest being 60 inches (152.4 cm.).

The cylinder is heated from below by four large Bunsen burners, each having a protractor stopcock, reading to degrees, for the ready regulation of gas flow. An outer cylinder of sheet iron serves as a hot-air jacket to the inner one. Four openings below in the outer casing admit the flames, and the same number above permit the escape of combustion products.

An air pipe at the side connects the inner cylinder with air-pumps and a mercury gage, and a second air pipe leads to a small iron side-cylinder, or heater, provided with graduated stopcocks, and joined to a series of drying flasks, generators of carbon dioxide, etc., according to the needs of the experiment.

The apparatus is shown in plan on a scale of 1–12 in fig. 7.

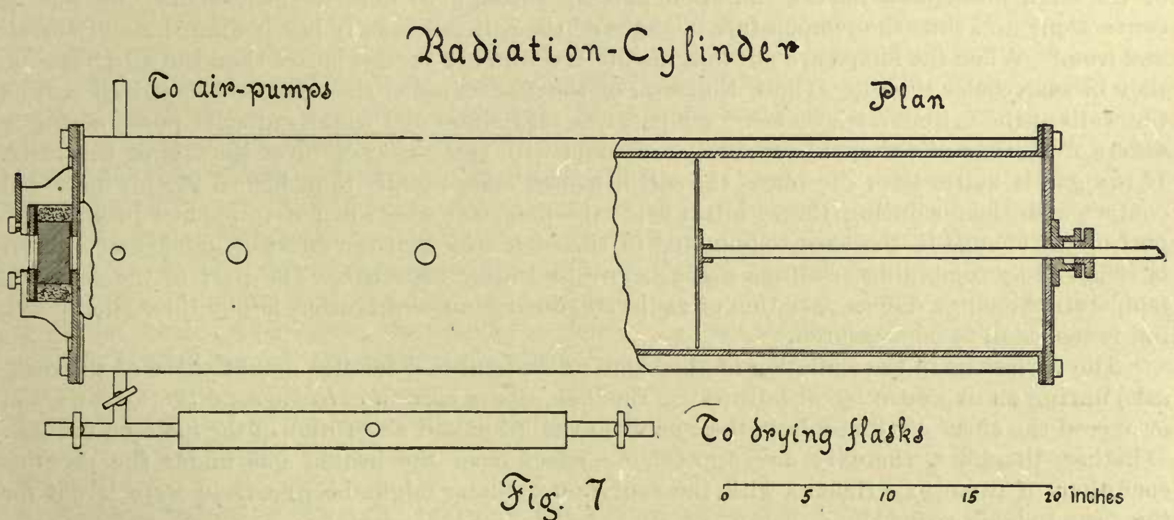

Fig. 7

The radiation cylinder has an approximate volume of 6,787 cubic inches = 111.3 liters, and holds about 144 grams of air at 760 mm. pressure and 0° C., containing, if unpurified, nearly 0.14

gram of carbon dioxide. The actual atmospheric pressure during the experiments was usually from 730 to 735 mm.

The bolometer is carried by a massive stand which permits accurate adjustment, and holds the instrument with a solidity which can not be improved. The mounting of the great cylinder in the first experiment was not so firm, but it was afterwards stiffened by braces and gave no further trouble. The entire apparatus stood on a stone pier.

The bolometer case was protected by the multiple tin-plate screens of small aperture, the outer screen being 2.46 in. from the front of the lead ring which clamps the rock-salt to the end-plate. In Jamin's "*Cours de physique*," 3e ed., tome 3, 3e fasc., p. 93, is an allusion to a source of error neglected in the otherwise very careful work of Melloni. The polished rock-salt plate reflects to the bolometer rays from a small annulus of the protecting screen, but the effect in my observations is very minute; first, because the polished tin plate does not absorb radiation well and is not much heated; second, because any rays which the screen may emit or reflect are only feebly reflected by polished rock-salt; third, because the angular aperture of the measuring instrument is small; and in general, since the gaseous radiation is measured by finding the change due to motion of an internal disk, the effect in question is constant at a given temperature, and without influence on the result.

GENERAL THEORY OF THE APPARATUS C.

When the disk in the heated apparatus is moved away from the bolometer, a deflection results which is made up (1) partly of positive gaseous radiation, (2) partly of diminished disk radiation due to greater gaseous absorption, (3) in part, of any change which takes place in rock-salt radiation, which may be either positive or negative, (4) of any change in the disk radiation due to its removal to a part of the cylinder having a different temperature. This also may be either positive or negative, and is quite appreciable if the cylinder is not uniformly heated, for instance, if one or more of the lamps are extinguished.

For the present purpose (2) need not be separated from (1). Absorption simply makes the gaseous radiation appear smaller. Considering (1) and (3), the rock-salt, if the supply of heat were equable, would tend to remain at a lower temperature, as a whole, than the gas within the cylinder, because the outer surface of the salt is cooled by contact with the outside air, and its entire substance radiates outwardly through a wide aperture. Nevertheless, since the thickness of the rock-salt plate is great, while its conductivity and radiative power are small, a very marked thermal gradient is produced within the salt, and in actual work its temperature is always changing. The air gets its heat chiefly by contact with the hot iron; the salt, on account of its small absorption of the radiation passing through it, gets its heat mainly by the air convection; and thus the temperature-changes of the salt continually lag behind those of the air and iron.* When the lamps are put out, the air and iron are at first hotter than the salt, but soon they become cooler than it. The withdrawal of the disk exposes the rock-salt to radiation from the walls of the cylinder, whose mean temperature may differ, and whose radiative power certainly differs from that of the disk, and also to contact with the gas swept over the face of the plate. If the gas is hotter than the plate, the salt is heated more rapidly than before by this increased contact with the air during the withdrawal of the disk, but also when it is pushed back. This part of the change is, therefore, eliminated in the same way that the effect of galvanometer drift is removed by combining readings made before and after exposure. The part of the rock-salt temperature-change due to variation of radiation during an observation is not thus eliminated, but is too small to be measured.

The variations in the radiation of the copper disk (and to a smaller extent those of the rock-salt) during an exposure by withdrawal of the disk, under certain extreme conditions, may equal or exceed the effect attributable to the combined radiation and absorption of the inclosed hot gas. Whether, therefore, there is any appreciable effect from the heated gas under the peculiar conditions of these experiments with the radiation cylinder might be uncertain were it not for the tests to be described.

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* For further details in respect to rock-salt radiation, see the first part of my article on "The Probable Range of Temperature on the Moon," *Astrophysical Journal*, vol. 8, p. 199, Nov., 1898.

We can not suppose that changes in the thermal condition of the solid parts of the apparatus are ever entirely absent; but since the sign of these variations of temperature is reversed in passing from heating to cooling conditions, it might be supposed that a mean between deflections obtained with a heating cylinder and those from a cooling one would be due to gaseous radiation and absorption, the effect of any possible changes in the copper disk canceling out, and those of the rock-salt being eliminated by the mode of exposure, as already shown; but it will be seen subsequently that this interpretation of the results is not permissible, and that the effect of another cause of discrepancy—that of imperfect homogeneity of the gaseous radiating column—must be considered.

When the radiation cylinder is heating, the temperatures of the well-stirred air being taken as abscissæ, the observed radiations, plotted as ordinates, fall accurately upon a straight line, radiation being proportional to excess. With a cooling cylinder the radiations are very much smaller, and fall on a curved line. It would be very easy here, from an incomplete or an imperfectly analyzed experiment, to draw erroneous conclusions.

The wrought-iron cylinder (except where the flame plays directly upon it), by virtue of its thermal conductivity, must be not very far from the mean temperature of the hot-air jacket (which has been measured), but lagging behind somewhat both in heating and cooling. The temperature of the air within the cylinder lags still more, because of its small conductivity. The cylindrical surface of iron to be heated has an area of 2,263 square inches. The direct impact of the flame is exerted upon not more than $\frac{1}{100}$ of this surface, and the play of a flame at 1,000° to 1,800° C. heats this portion unduly, a considerable area of the floor of the radiation cylinder having, by conduction, more than the average temperature. Columns of hot air rise within the cylinder along its central axis during heating, over each of these hot places, and these columns, much hotter than the mean temperature of the air within the cylinder (which mean temperature is alone given by the thermometer), produce the larger deflections during heating. The supposition that change of temperature of the rock-salt has anything to do with the deflection has been shown to be untenable, and is most completely negatived when it is known that the total radiation of the salt is less than that represented by the deflection in question, while the temperature of rock-salt, and thence its radiation, changes very slowly. Variations of temperature in the copper disk in its two positions may produce considerable deflections, but only under extreme conditions which are not those of the actual experiment. Substitution of a blackened asbestos disk, a bad conductor of heat, in place of the conductive copper, also makes little difference in the result with a cooling cylinder, unless the temperature distribution is abnormal. The deflections obtained in the ordinary working can, therefore, only be due to the changing dimensions and temperatures of the hot-air columns within the cylinder; and the fact that there is a larger radiation at a given mean temperature, as indicated by the thermometer, when the temperature of the cylinder is increasing, together with the observed relation between the rapidity of the heating and the amount of the radiative excess over the measurement with a cooling cylinder, the deviation being greater the more rapid the heating, testify that the radiation comes from a body subject to the internal changes and irregular structure produced by convection; and an effect which at first sight may seem anomalous becomes a proof that the radiation observed is really that of the air, and is not due to any change in the thermal condition of the solid parts of the apparatus during exposure. In passing from the condition of a heating cylinder to that of a cooling one, with but slight change of average temperature, there is a continuous fall of radiation, that for the stationary point being less than for increasing temperature, but more than for falling temperature.

When heated from below, the central region of an inclosed fluid is occupied by ascending columns heated beyond the mean temperature of the mass, while during cooling the central currents are cooler than the average. This central region in the present case is the only one observed by means of the bolometer whose indications do not give the average radiation of all the air in the cylinder, but that of the rapidly moving and thermally varying portion included within the central cone of rays.

The composition of the axial radiating air column when heating may be analyzed, probably with some approximation to the truth, as follows: Suppose that nine-tenths of the air in the horizontal stretch of this axial line have a temperature of 90° and radiate with an intensity of

4 for each tenth, or 36 in all, while one-tenth is air just rising by convection and heated to 250° by contact with the hot iron. The radiative power of this tenth may be taken as 85, and the total radiation is 121; whereas the radiation of a body of air at mean temperature

$$\frac{(9 \times 90) + 250}{10} = 106^\circ$$

will be about 68 on the same scale, and the observed radiation is nearly double that appertaining to the given mean temperature.

When the disk is "in"—*i. e.*, at its nearest approach to the rock-salt plate, while the temperature is increasing, the thermometer of the radiation cylinder is partially separated from the larger part of the interior space and from the chief source of heat supply. The reading of the thermometer is therefore lower, since the ends of the cylinder cool faster. But even with the disk out, the thermometer reading is too low, as is shown by a rise of several degrees after a quick movement of the disk to and fro several times when the heating cylinder has not been recently stirred. After about ten minutes of cooling, however, with less frequent agitation, no change in the thermometer reading occurs after stirring. The distribution of temperature is therefore more equable during cooling. The thermometer, after vigorous stirring of the air, records its true temperature, as in the use of the sling thermometer.

In order to get the thermometer out of the line of radiation, it had to be lifted a little above the central axis of the cylinder. Hence, without mixture of the air layers, the reading should have been too low in heating, too high in cooling. (See thermal diagrams.) The last error, however, is inappreciable, and I think we may see why from the following considerations: When heating, the metal at the bottom of the cylinder is quite hot; that at the top much cooler. The air is heated by contact at the bottom, and being thus lighter and in unstable equilibrium, it rises and carries heat to the middle space, mixing with cooler air until its ascension is stopped by the top wall, and great diversity of temperature prevails. For example, internal air in immediate contact with the iron top and bottom walls being at 50° and 250°, respectively, an air temperature of 90° should be found at some point in the upper half of the air space when the mean temperature of the entire mass of air is 110°, ascending thirds of the air being on the average 150°, 100°, 80°. Stirring may then cause a rise of 20°, as has actually occurred, and streaks of air as hot as 200° may reach the central line, contributing more than their share to the total radiation on account of their relatively greater radiative power.

The following centigrade temperatures of the hot-air jacket of the radiating cylinder were observed (temperature rising):

		°
Jacket:	At the top, near center	257
	" " " " end	250
	" " side " "	140
	" " bottom " "	56

$$\left.\begin{array}{l} \text{Upper half, } \dfrac{254 + 140}{2} = 197^\circ \\[2ex] \text{Lower half, } \dfrac{140 + 56}{2} = 98 \end{array}\right\} \text{Mean} = 148$$

Temperature of air within the radiation cylinder $= 110^\circ$.

A hypothetical vertical thermal section of the air in the cylinder is indicated in the diagram:

$$\begin{array}{|ll|} \hline \text{Top wall of cylinder} & 50^\circ \\ \text{Internal air} & 90^\circ \left\{ \begin{array}{c} 80 \\ 100 \\ 150 \end{array} \right\} 110^\circ \\ \text{Bottom wall} & 250 \\ \hline \end{array}$$

The cooling of the metal after the lamps are extinguished is chiefly from beneath by convection currents, which rush upward through the space between the radiation cylinder and the outer jacket, while the air within the cylinder is cooled by contact with the metal at the top, whose temperature differs less than before from the bottom temperature, and little change is suffered by the air from contact with the cooler metal at the bottom on account of the feeble conductivity of air and stagnation by greater density there. Thus the distribution of temperature in cooling may be this: Air in immediate contact with iron, 110° and 75° at top and bottom, respectively. Air temperature by ascending thirds: 105°, 110°, 115°. Mean, as before, 110°.

The following temperatures of the hot-air jacket were observed after the preceding ones, but with a cooling cylinder, all of the lamps but one (the second from the rock-salt) having been extinguished:

		°
Jacket·	At the top, near center	129
	" " " " end	117
	" " side " "	95
	" " bottom " "	56

$$\left.\begin{array}{l}\text{Upper half, } \dfrac{123 + 95}{2} = 109^{\circ} \\[2ex] \text{Lower half, } \dfrac{95 + 56}{2} = 75.5\end{array}\right\}\text{Mean} = 92$$

Internal temperature of radiation cylinder = 110°.

A hypothetical internal vertical temperature distribution in close agreement with these observations is shown in the diagram:

			°	
Top wall of cylinder			110	
Internal air		$112^{\circ}.5\left\{\begin{array}{l}115\\110\end{array}\right.$		$\left.\begin{array}{l}115\\110\\105\end{array}\right\}110^{\circ}$
Bottom wall			75	

Here all layers of air have nearly the same temperature. The position of the internal thermometer is of little consequence, and small change results from stirring.

Curves of radiation and temperature with a cooling cylinder pass so nearly through the points of observation after prolonged stationary temperature that no great error will be committed by assuming the cooling observations to be correct after cooling has progressed for a little time.

That the larger radiations during rapid heating are abnormal, and indicate excessive heating of the bottom of the cylinder and of the lowest layers of gas, is proved by the fact that under these circumstances the apparent mean temperature of the gas, on putting out the lamps, does not vary much during many successive stirrings, although the deflections diminish continually until the customary reading corresponding to that temperature and uniform distribution of heat is reached, after which the thermometer begins to fall rapidly and the radiation to diminish according to the usual law.

Example: Cylinder containing carbon dioxide. After heating for several hours the lamps were put out and readings taken during initial cooling. Battery galvanometer, 113 div., but here all deflections have been reduced to standard current. Each deflection in this and the following experiments, unless otherwise specified, is the mean of five concordant readings.

All temperature-excesses are reckoned from the temperature of the bolometer, there being no other standard possible in the mode of exposure followed, and are given in centigrade degrees. Pressure in closed cylinder varying from 744 mm. to 718 mm., mean 731 mm. (reduced to freezing point). Temperature of room, 30°.2; of bolometer, 35°.2; dew-point, 13°.9 C.

TABLE 26.

Heating rate per minute.		Temperature.	Excess.	Radiation.
	°	°	°	*Divisions.*
Series 1:	+0.83	132.6	97.4	+19.2 (abnormal)
Lamps out		133.2 Max.	98.0	
After 3 min.	—0.13	133.0	97.8	+15.7 "
" 7 "	—0.73	131.4	96.2	+12.4 "
" 12 "	—1.10	125.5	90.3	+ 8.7 (normal)
Series 2 (after further heating)	± 0	127.4	92.2	+16.5 (abnormal)
Lamps out		136.2 Max.	101.0	
After 5 min. cooling	—0.36	135.3	100.1	+14.5 "
" 10 " "	—1.23	126.9	91.7	+ 9.5 (normal)

The last and subsequent readings of each series are normal, the temperature, as indicated by the internal thermometer, diminishing rapidly.

A similar result has been obtained in the use of an asbestos disk, but here other causes assisted. To determine what change, if any, would take place if the radiative disk were nonconducting, the copper had been covered with blackened asbestos on the side facing the rock-salt window. With a heating cylinder the *apparent* air radiation was greater when the nonconducting disk was used, and much greater when only the two central lamps were lighted and the ends of the cylinder were at lower temperatures than under normal conditions, even although the duration of the experiment was prolonged until a stationary mean temperature was reached. The surface chilling of the disk in the forward position—*i. e.*, nearest to the rock-salt, increased the deflection, and the effect persisted until the difference of temperature between the middle and the ends of the cylinder ceased. The abnormal results at maximum temperature and during initial cooling, while the apparent or recorded mean temperature is nearly stationary, are in this case due to the combined effect of vertical and horizontal inequality of temperature.

Example: Cylinder filled with air at atmospheric pressure, thoroughly dried by phosphoric anhydride, and purified from carbon dioxide. After heating continuously for 23 hours the recorded mean stationary temperature was 68°.9. The two middle lamps were then turned up for 1 minute, until the temperature had risen to 71°, when the lamps were extinguished.

TABLE 27.

Heating rate per minute.		Temperature.	Excess.	Radiation.
	°	°	°	*Divisions.*
	+2.1	70.0	38.0	+8.0 (abnormal)
Lamps out		71.0 max.	39.0	
After 4 min. cooling	±0.0	71.0	39.0	+7.5 "
" 8 " "	±0.0	71.0	39.0	+5.8 "
" 12 " "	—0.12	70.8	38.8	+4.6 "
" 16 " "	—0.28	70.0	38.0	+3.9 "
" 20 " "	—0.10	69.2	37.2	+2.8 (normal)

Here, after prolonged but unequal heating, 20 minutes of cooling were required to give the approximation to a normal value, recorded in the last line, the first reading being nearly three times too large.

The preceding example was obtained after all parts of the cylinder had become well heated, the inequalities of thermal distribution being comparatively small. The next experiments show the extraordinary increments produced by the use of the asbestos disk with a rapidly heating cylinder. The air within the cylinder was approximately dry, and purified from carbon dioxide. Two middle burners were lighted, with cocks set at 30 div.

TABLE 28.

Heating rate per minute.	Temperature.	Excess.	Radiation.
°	°	°	*Divisions.*
+1.2	62.4	25.8	+ 8.4
+1.4	72.5	35.9	+16.2
+1.8	80.3	43.7	+20.9
+2.1	90.0	53.4	+24.6
+2.6	100.3	63.7	+30.6
+2.0	108.9	72.3	+35.5

The deflections are here four to six times as great as those with a cooling cylinder. A repetition of the experiment gave the results in Table 29.

TABLE 29.

Heating rate per minute.	Temperature.	Excess.	Radiation.
°	°	°	*Divisions.*
+3.6	61.8	28.2	+13.4
+2.4	70.8	37.2	+17.3
+4.0	81.0	47.4	+25.0
+4.2	90.9	57.3	+26.1
+2.8	100.2	66.6	+32.6
+2.0	110.2	76.6	+37.7

The observations may be represented by a straight line passing through the origin and a deflection of 30 div. at excess 63°, giving a mean deflection of 0.476 div. per degree of excess. The ratios to the deflections of the cooling curve are, as before, about six to one at the middle of the heating curve, where the rate of heating is greatest.

The asbestos in the forward position radiates to the cooler iron of the end-plate, and hence becomes cooler. When withdrawn to the rear the blackened surface of the asbestos absorbs radiation from the hot interior, and is also heated by contact with hotter gas; but, although the copper back is now near a cooler end-plate, the nonconductivity of asbestos prevents any influence from this cause. The positive differential effect is added to the true gaseous radiation. The conductivity of copper, and the more equable distribution of temperature in the metal walls, prevent any but a small temperature-change in the copper disk during the time of an observation in the normal working of the heating cylinder, and the larger deflections with heating cylinder are in this case due almost entirely to inequality of gaseous temperature, as is shown by the closer agreement of the readings, after prolonged heating to a stationary temperature, with those of the cooling curve; but the results with asbestos, under the same circumstances, are different. When the lamps are put out, the distribution of temperature in the cooling iron, after a time, becomes nearly uniform, the increase of 200 or 300 per cent. in the apparent gaseous radiation with stationary mean temperature, due really to temporary chilling and heating of the surface of the blackened asbestos, then ceases, and the values of air radiation, observed with a cooling cylinder, are nearly the same with an asbestos disk as with copper. These measures may therefore be included with those from which the final curves of air radiation are derived. The abnormal values which have been purposely obtained by varying the method and conditions of working, are only used to arrive at an understanding of the meaning of the ordinary results, and to derive some indication as to their reliability. Many things which were puzzling at the time the experiments were made are now clear to me, and I hope that they will be so to the reader who has the patience to follow the details of a research beset with difficulties and intricacies.

The following experiment with the blackened copper disk exhibits the result of a still wider departure from normal conditions, and bears witness to the necessity of some of the precautions

which were taken in the ordinary use of the apparatus. In heating the hot-air jacket around the radiation cylinder, four large Bunsen burners are customarily employed, their positions being such as to secure as uniform distribution of temperature as possible within the cylinder with the given means. With only one lamp lighted, the effects are very different, according to the position of the lamp. When the single lamp was at the end farthest from the rock-salt, there was a positive deflection. The mean temperature of the inclosed air had been so regulated that it was falling, a condition ordinarily attended by smaller galvanometer readings. On the other hand, when the single lamp was at the rock-salt end, the deflection became negative with a heating cylinder, which ordinarily gives increased readings.

The observation follows: Battery current, standard, or 100 div. Temperature of room, 26°; of bolometer, 31°; dew-point, 11°.7, corresponding to a pressure of aqueous vapor of 10.23 mm. or 10.28 grams per cubic meter, and to an equivalent liquid depth of 0.000 387 cm. in the absorbent layer.

(*a*) Fourth lamp (farthest from the rock-salt) lighted. Burner cock set at 30 div. Temperature of air in cylinder read immediately after vigorous stirring:

	°
Temperature before experiment	102.2
" after "	97.8
mean =	100.0
Excess =	69.0

Cooling rate, 0°.88 per minute; mean differential radiation (disk shifted from 0.35 to 5.0 feet) = + 7.80 div.

(*b*) First lamp (nearest to rock-salt) lighted. Burner cock set at 35 div. The other lamp put out.

	°
Temperature before experiment,	104. 6
Temperature after experiment,	108. 0
Mean, =	106. 3
Excess, =	75. 3

Heating rate, 0°.68 per minute. Mean differential radiation (disk shifted as before) = − 1.34 div.

Analyzing the component sources of radiation in these two experiments, and neglecting absorption, it will be seen that in (*a*) the copper disk was getting hotter when "out," and was cooling when "in," or at the end next to the rock-salt. Its thermal change had the same sign as the hot-air radiation during exposure of the air column. The front walls of the cylinder were cooler than the rear walls, and cooler than the copper disk, since the latter evidently suffered not merely a halt in its thermal increment, when at the front, but a decided decrement of heat. Changes in the temperature of the rock-salt contributed to the combined effect, although only to a slight degree, since the radiating power of the rock-salt plate was but one-fourth that of blackened copper at the same temperature, and its rate of change very slow. When the warm copper disk was pulled out, the salt received radiation from the front walls of the iron cylinder, far from the flame, and certainly cooler than the frequently heated copper, also less powerfully emissive. At the same time, cooler descending internal convection currents played upon the salt, cooling it, while the disk was getting hotter. The thermal change of the salt was, therefore, opposite to that of the copper.

In experiment (*b*) the copper disk was heated at the front and was cooling while at the farther end. Its change of radiation was therefore of the opposite sign to the always positive radiation of the column of heated air (disk out), and since the rock-salt (disk out) was exposed to the radiation of neighboring walls hotter than the disk, and also to the warmer internal convection currents which then ascended at the front, the thermal change of the salt again had the opposite sign to that of the disk.

If δc = the variation of radiation dependent upon thermal change in the black copper in the time of exposure,

δs = the corresponding variation depending upon thermal change in the rock-salt, modified by its own absorption,

r = the mean radiation of the hot air, as affected by self-absorption and assumed to be constant,

x = the transmission of hot air radiation by salt,

y = the transmission of the radiation of black copper by hot air and salt,

z = the transmission of the composite radiant beam issuing from the rock-salt, exercised by the air between the salt and the bolometer,

we may express the facts of these experiments thus:

$$(a) \qquad z\,(xr + y\delta c - \delta s) = +\,7.80$$
$$(b) \qquad z\,(xr - y\delta c + \delta s) = -\,1.34$$

The change of radiation of the rock-salt in a quiescent atmosphere has been found quite inappreciable during the time of exposure, and, although somewhat larger under strong convection currents, it is still a very small quantity; but for illustration it may be included, taking $\delta s = \frac{1}{50}\,y\delta c$. The equations give

Constant radiation of hot air	xzr	$= +\,3.23$
Variation due to thermal change in copper	$yz\delta c$	$= \pm\,4.66$
Variation due to thermal change in salt	$z\delta s$	$= \pm\,0.09$

The total radiation of black copper, rock-salt, and air on this occasion was found to be 52.3 div., the excess being 74°. This radiation is made up approximately of—

Radiation of black copper, transmitted by salt	39.3
Radiation of air, transmitted by salt	3.2
Radiation of rock-salt	9.8

The rock-salt plate having absorbed one-fourth of the original radiation from the interior, the initial deflections before absorption may have been:

Blackened copper	$39.3 + 13.1 = 52.4$
Air	$3.2 + 1.1 = 4.3$

The indicated radiation for the blackened copper is not far from normal, but the air radiation is only a little over one-third of that obtained by the usual method, no doubt because, with but one lamp burning, only a part of the air is effective, the distribution of temperature being far from uniform, as the variation in the temperature of the copper disk at opposite ends of the cylinder also proves.

The influence of self-absorption of its own radiations by a gas brings into play another factor which changes with the depth of the gaseous layer. By varying the play of the disk in exposure, this feature may be partly determined, but its complete elucidation demands apparatus with a great range of dimensions.

Paschen ("Ueber die Emission der Gase," *Wied. Ann.*, Bd. 51, S. 30, 1894) finds that a 7-cm. layer of carbon dioxide absorbs at the position of its chief band "like an infinitely thick layer," and that the absorption of aqueous vapor is by no means proportional to the depth, but increases (at wave length $2.60\,\mu$) from 60 per cent. to 80 per cent., when the depth of the vaporous layer varies from 7 cm. to 33 cm. (*loc. cit.*, p. 12). Hence, gaseous radiant emission is not proportional to the depth, except for small depths, and it is conceivable that there may be, for a given depth, some temperature of the gas at which there is such a compensation of emission by absorption that increase of thickness will not affect the quantity—disk radiation plus gaseous radiation plus gaseous absorption. In fact, Paschen's fig. 8 (Taf. 1, *Wied. Ann.*, Bd. 51) shows that the ratio of gaseous emission to gaseous absorption for carbon dioxide changes with the temperature, and the same figure permits a determination of one point on a curve of compensation of radiation by absorption for this gas.

The first measurements made with apparatus C were to find the relation between air radiation and depth, and to these we may now pass.

METHOD C.—EXPERIMENTS IN WHICH THE DEPTH AND PRESSURE OF THE AIR HAVE BEEN VARIED.

Each of the two air-pumps diminished the pressure in the cylinder by about 100 mm. with the first 20 strokes; but owing to the slow action of the valves, it was difficult to get the final pressure below 50 mm., although the pumps worked well enough when the receiver to be exhausted was small. In addition to this trouble, there has always been some leakage at low pressures—*e. g.*, in one experiment where the air temperature did not exceed 100° C., the gage at $4^h\ 27^m$ read 94.6; at $5^h\ 32^m$ the reading was 98.4 mm., the pressure having risen 3.8 mm. in 65^m, or 0.059 mm. per minute, and fresh leaks have frequently started from the strain of heating. Consequently, in experiments with partial vacuum, it has been necessary to work rapidly, and in spite of drying flasks, some aqueous vapor must enter through leakage. The final method which overcame this difficulty was the introduction of a bowl of phosphoric anhydride within the cylinder. After repeated exhaustions, allowing air to flow into the cylinder through a series of flasks containing porous chloride of calcium, experiments were commenced January 25, 1893, with air nearly dry, but still containing carbon dioxide in the usual small proportion. Without further announcement, it may be understood that in all the readings which follow, the deflections have been reduced to standard conditions of current and bridge. The change is usually very small, but in the present case, with battery galvanometer 95 div., the arrangement of the bridge was insensitive, and the multiplier is 2.0. Mean temperature of room, 20°; of bolometer, 25°; dew-point, 12°.2. Pressure of aqueous vapor, 10.57 mm., or 10.71 grams per cubic meter. The absorbent layer contained enough water to make a liquid depth of 0.000 403 cm. The disk was set at even feet, but the initial reading with which comparison is to be made is that of the shortest air column, 0.35 feet. The measurements were made at both ordinary and low pressures.

TABLE 30.

Position of disk, feet.		0.35.	1.	2.	3.	4.	5.	Temperature.	Excess.	Pressure.
Air depth	ft.	0	0.65	1.65	2.65	3.65	4.65			
	cm.	0	19.8	50.3	80.8	111.3	141.8			
			div.	*div.*	*div.*	*div.*	*div.*			
Deflections		0	4.8	15.0	23.2	35.4	33.6	170°	145°	95mm.
		0	6.0	15.8	24.0	32.6	32.0	185.5	160.5	723
Mean deflection		0	5.4	15.4	23.6	34.0	32.8			
Change per foot		....	8.3	10.0	8.2	10.4	—1.2			

The two series in this table, taken at pressures which vary in the ratio of 1 : 7.6, are almost identical. The discussion of this at first sight rather startling fact is reserved for a subsequent section. Except for the last foot the increase of radiation is proportional to the depth. In view of what has been said as to the effect of unequal distribution of temperature it might be suspected that the diminished deflection at the fifth foot comes from the chilling of the disk by proximity with the cooler end-plate, but this is not the true explanation, as the next example demonstrates.

TABLE 31.

Cylinder filled with dry carbon dioxide.

Position, feet.		0.35	1.	2.	3.	4.	5.	Temperature.	Excess.	Pressure.
Depth	ft.	0	0.65	1.65	2.65	3.65	4.65			
	cm.	0	19.8	50.3	80.8	111.3	141.8			
Mean deflection (div.)		0	3.5	7.6	10.4	10.5	10.2	142°.7	125°.8	766mm.
Change per foot		....	5.4	4.1	2.8	0.1	—0.3			

Two things are shown clearly by these concise tables, namely, that, allowing for the difference of temperature, the apparent radiation of carbon dioxide is smaller than that of dry air at temperatures not exceeding 200° C. and that the law of increase of radiation with the depth is entirely different for these two substances. To make the last point quite certain, the experiment was repeated with dry carbon dioxide, first at atmospheric pressure and then at low pressure. These measures are given in full as an example of the mode of observation.

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Each complete observation consists of three successive series, of ten readings each, with differential depths of carbon dioxide gas of 4.65 feet, 1.65 feet, and again 4.65 feet, the middle series being contrasted with the mean of the extremes to eliminate the variation from change of temperature. Each deflection is from three galvanometer readings, with disk in, out, and in again, and is complete in itself.

Battery galvanometer, 100 div. Barometer, 734 mm., which is the pressure of the gas in the first three series. Temperature of the bolometer, assumed to be 5° hotter than the reading of the dry-bulb thermometer placed beside the bolometer case. The temperature of the bolometer is taken as the initial or comparison temperature.

At $11^h\ 9^m$, dry bulb = 63°.8 F. = 17°.7 C.
wet bulb = 55°.1 F. = 12°.8 C.

Difference, 8.7 + 4.4 (correction for unventilated psychrometer of 50 per cent.) = 13°.1 F. Dew-point, 38° F. Relative humidity, 0.38. Temperature of radiation cylinder = 121°.0 C.

TABLE 32.

(Series 1.)

Position of disk.			Mean in.	Deflection.
In.	Out.	In.		
Depth of gas (feet).				
0.35	5.0	0.35		
				div.
105.1	113.0	104.1	104.6	+8.4
104.1	112.0	105.2	104.7	+7.3
106.1	113.3	103.4	104.8	+8.5
105.0	112.6	108.0	106.5	+6.1
100.0	109.5	103.0	101.5	+8.0
103.0	114.2	105.8	104.4	+9.8
106.1	114.2	105.8	106.0	+8.2
103.0	112.1	102.5	102.8	+9.3
102.5	111.4	103.0	102.8	+8.6
103.0	112.2	104.0	103.5	+8.7
Differential radiation for depth (4.65 ft.).				+8.29

At $11^h\ 19^m$, dry bulb = 65°.0 F. = 18°.3 C.
wet " = 56°.0 F. = 13°.3 C.
Difference = 9.0 + 4.5 (correction) = 13°.5 F.
Dew-point, 38° F. Relative humidity, 0.37.
Temperature of radiation cylinder = 126°.8 C.
Mean temperature of radiation cylinder (series 1) = 123°.9 C.
" " " excess (series 1) = 100°.9 C.

Mean dew-point, 38° F. = 3°.3 C., or pressure of aqueous vapor = 5.78 mm., corresponding to 6.04 grams of water per cubic meter of air, and to an equivalent depth of liquid water of 0.000 227 cm. in the absorbent air layer. At $11^h\ 25^m$, temperature of radiation cylinder = 133°.0 C.

TABLE 33.

(Series 2.)

Position of disk. In. Depth of gas (feet). 0.35	Out. 2.0	In. 0.35	Mean in.	Deflection.
				div.
100.0	109.1	103.8	101.9	+7.2
99.2	107.7	100.8	100.0	+7.7
100.8	109.6	103.8	102.3	+7.3
102.7	111.1	105.5	104.1	+7.0
105.5	114.0	107.0	106.3	+7.7
102.0	112.0	105.7	103.9	+8.1
105.9	112.8	108.0	107.0	+5.8
97.8	105.0	98.2	98.0	+7.0
98.2	108.1	102.6	100.4	+7.7
102.6	111.0	101.9	102.3	+8.7
Differential radiation for depth (1.65 ft.).				+7.42

At $11^h\ 33^m$, dry bulb = 65°.9 F. = 18°.8 C.

wet " = 57°.0 F. = 13°.9 C.

Difference = 8.9 + 4.5 (correction) = 13°.4 F.

Dew-point, 40° F. Relative humidity, 0.38.

Temperature of radiation cylinder = 143°.2 C.

Mean temperature of radiation cylinder (series 2) = 138°.1 C.

" " " excess " = 114°.5 C.

Mean dew-point, 39° F. = 3.9° C., or pressure of aqueous vapor = 6.03 mm., corresponding to 6.23 grams per cubic meter of air, and to an equivalent depth of liquid water of 0.000 234 cm. in the absorbent air layer.

TABLE 34.

(Series 3.)

Position of disk. In. Depth of gas (feet). 0.35	Out. 5.0	In. 0.35	Mean in.	Deflection.
				div.
105.3	116.8	105.0	105.2	+11.6
105.0	120.0	106.8	105.9	+14.1
106.0	118.2	107.1	106.6	+11.6
107.1	119.0	109.0	108.1	+10.9
101.6	112.3	101.0	101.3	+11.0
101.0	112.0	101.8	101.4	+10.6
101.8	112.9	102.0	101.9	+11.0
102.0	115.0	101.8	101.9	+13.1
103.0	116.0	102.8	102.9	+13.1
102.8	115.0	103.7	103.3	+11.7
Differential radiation for depth (4.65 ft.).				+11.87

At 11ʰ 43ᵐ, dry bulb = 66°.8 F. = 19°.3 C.
wet " = 57°.4 F. = 14°.1 C.
Difference = 9.4 + 4.7 (correction) = 14°.1 F.
Dew-point, 40° F. Relative humidity, 0.37.
Temperature of radiation cylinder = 146°.7 C.
Mean temperature of radiation cylinder (series 3) = 145°.0 C.
" " " excess " = 120°.9 C.

Mean dew-point, 40° F. = 4°.4 C., or pressure of aqueous vapor = 6.24 mm., corresponding to 6.50 grams per cubic meter of air, and to an equivalent depth of liquid water of 0.000 244 cm. in the absorbent layer of air.

The cylinder was now partially exhausted for the low-pressure experiments.

At 12ʰ 6ᵐ, dry bulb = 68°.0 F. = 20°.0 C.
wet " = 59°.0 F. = 15°.0 C.
Difference = 9.0 + 4.5 (correction) = 13°.5 F.
Dew-point, 43° F. Relative humidity, 0.40.
Temperature of radiation cylinder = 149°.9 C.
Pressure in " " = 85 mm.

TABLE 35.

(Series 4.)

Position of disk. In. — Depth of gas (feet). 0.35	Out. — 5.0	In. — 0.35	Mean in.	Deflection.
				div.
93.8	105.0	93.2	93.5	+11.5
93.2	105.1	90.7	92.0	+13.1
90.7	103.2	91.5	91.1	+12.1
91.5	103.5	92.2	91.9	+11.6
92.2	105.0	92.0	92.1	+12.9
92.0	102.0	91.2	91.6	+10.4
91.2	104.1	88.0	89.6	+14.5
88.6	102.1	87.4	88.0	+14.1
87.4	101.1	86.8	87.1	+14.0
86.8	99.4	86.1	86.5	+12.9
Differential radiation for depth (4.65 ft.).				+12.71

At 12ʰ 12ᵐ, dry bulb = 68°.8 F. = 20°.4 C.
wet " = 59°.8 F. = 15°.4 C.
Difference = 9.0 + 4.5 (correction) = 13°.5 F.
Dew-point, 45° F. Relative humidity, 0.41.
Temperature of radiation cylinder = 154°.0 C.
Mean temperature of radiation cylinder (series 4) = 152°.0 C.
" " " excess (series 4) = 126°.8 C.

Mean dew-point, 44° F. = 6°.7 C., or pressure of aqueous vapor = 7.31 mm., corresponding to 7.55 grams per cubic meter of air, and to an equivalent depth of liquid water of 0.000 284 cm. in the absorbent layer of air.

Pressure of carbon dioxide, 85 mm.

TABLE 36.

(Series 5.)

Position of disk. In. Depth of gas (feet). 0.35	Out. 2.0	In. 0.35	Mean in.	Deflection.
				div.
99.0	109.6	100.2	99.6	+10.0
103.3	112.9	101.9	102.6	+10.3
101 9	114.0	103.9	102.9	+11.1
97.2	108.4	97.0	97.1	+11.3
100.2	108.5	99.6	99.9	+ 8.6
100.0	111.4	101.8	100.9	+10.5
101.8	112.2	104.4	103.1	+ 9.1
99.0	109.8	100.2	99.6	+10.2
100.2	109.2	101.3	100.8	+ 8.4
100.5	111.1	103.2	101.9	+ 9.2
Differential radiation for depth (1.65 ft.).				+ 9.87

At $12^h\ 19^m$, dry bulb = 69°.1 F. = 20°.6 C.
wet bulb = 58°.6 F. = 14°.8 C.
Difference = 10.5 + 5.3 (correction) = 15°.8 F.
Dew-point, 38° F. Relative humidity, 0.32.
Temperature of radiation cylinder = 163°.8 C.
Mean temperature of radiation cylinder (series 5) = 158°.9 C.
" " " excess (series 5) = 133°.4 C.

Mean dew-point, 41°.5 F. = 5°.3 C., or pressure of aqueous vapor = 6.64 mm., corresponding to 6.90 grams per cubic meter of air, and to an equivalent depth of liquid water of 0.000 259 cm in the absorbent layer of air.

Pressure of carbon dioxide = 91 mm.
Mean pressure of carbon dioxide (series 5) = 88 mm.

TABLE 37.

(Series 6.)

Position of disk. In. Depth of gas (feet). 0.35	Out. 5.0	In. 0.35	Mean in.	Deflection.
				div.
103.0	113.0	99.3	101.2	+11.8
99.3	112.3	99.3	99.3	+13.0
99.3	111.0	97.3	98.3	+12.7
97.3	111.2	94.9	96.1	+15.1
94.9	108.2	95.0	95.0	+13.2
95.0	107.6	94.0	94.5	+13.1
94.0	110.0	94.1	94.1	+15.9
94.1	108.9	92.5	93.3	+15.6
92.5	108.8	93.0	92.8	+16.0
93.0	107.2	92.0	92.5	+14.7
Differential radiation for depth (4.65 ft).				+14.11

At $12^h\ 26^m$, dry bulb = 69°.8 F. = 21°.0 C.
wet bulb = 60°.2 F. = 15°.7 C.
Difference = 9.6 + 4.8 (correction) = 14°.4 F.
Dew-point, 43° F. Relative humidity, 0.38.
Temperature of radiation cylinder = 164°.8 C.
Mean temperature of radiation cylinder (series 6) = 164°.3 C.
" " " excess (series 6) = 138°.5 C.

Mean dew-point 40°.5 F. = 4°.7 C., or pressure of aqueous vapor = 6.37 mm., corresponding to 6.63 grams per cubic meter of air, and to an equivalent depth of liquid water of 0.000 249 cm. in the absorbent layer of air.

Pressure of carbon dioxide = 96 mm.
Mean pressure of carbon dioxide (series 6) = 93.5 mm.

TABLE 38.—*Summary.*

Series.	Air layer.		Carbon dioxide in radiation cylinder.					
	Pressure.	Water cm. × 10 —⁶	Tempera-ture.	Excess.	Pressure.	Radiation.		Ratio δ 4.65 ÷ δ 1.65
						δ 4.65 ft.	δ 1.65 ft.	
	mm.		°	°	*mm.*	*dir.*	*dir.*	
1	734	227	123.9	100.9	734	8.29		
2	734	234	138.1	114.5	734		7.42	$\frac{10.08}{7.42}$
3	734	244	145.0	120.9	734	11.87		= 1.358
4	734	284	152.0	126.8	85	12.71		
5	734	259	158.9	133.4	88		9.87	$\frac{13.41}{9.87}$
6	734	249	164.3	138.5	93.5	14.11		= 1.359

As in the case of air, there is scarcely any difference in the radiation which can be attributed to change of pressure. The change of radiation with the depth is also unaffected by pressure. When the depth is increased in the ratio $\frac{4.65}{1.65} = 2.818$, the differential deflection is only increased in the ratio 1:1.359. Table 31 gives for the same depths the ratio of deflections $\frac{10.2}{7.6} = 1.342$, and the results of Table 31 for the 2d and 5th feet are confirmed by the more elaborate measures of Table 38.

Professor Paschen ("Emission erhitzer Gase," *Wied. Ann.*, Bd. 50, Taf. 9, fig. 9, 1893) gives a series of spectral energy-curves for the principal maximum of carbon dioxide at temperatures 110°, 158°, 330°, 622°, 710°, and 973° C., the radiation proceeding from a layer of the heated gas about 3 mm. deep. At the lowest temperature, which is a little below the highest in my observations, the deflections are very small, and the spectral energy-curve is very flat, but is still shown as a distinctly limited emission-band whose extreme wave-lengths do not differ by more than a fraction of a micron. Measuring the areas of the first four curves of Paschen's figure, the relative radiations are found to be—

Temperature	110°	158°	330°	622°
Radiation *	75	227	1,630	4,905

Drawing a curve through these values, and also (anticipating a little) one to represent my final measures of the total apparent radiant emission, the depths of radiant gas being 3 mm. and

* Measured in arbitrary units.

1,418 mm., the following approximate relative radiations for moderate temperature-excesses have been read from the curves:

TABLE 39.

Depth.	$t=20°$	$t=40°$	$t=60°$	$t=80°$	$t=100°$	$t=120°$
cm.						
0.3	1	4	12	30	59	100
141.8	2	7	17	36	65	100

The rate of increase of radiation with that of temperature is greater for a 3-mm. layer than for one of 1,418 mm., because the absorption in the mass of great depth partly neutralizes its own radiation. This is proved by the preceding experiments, which have demonstrated that a 5-foot layer of carbon dioxide radiates but little more than a 2-foot layer, and no more than a 3-foot layer. The rate of increase of radiation with temperature for a 5-foot layer of air does not differ much from the corresponding rate for carbon dioxide at these low temperatures, and the absolute radiations also are not very different; but, unlike carbon dioxide, the air radiates in proportion to the depth. It may be that this is because the measured radiation of air in my final experiments has been to a considerable extent that of its oxygen, nitrogen, or argon, and not merely that of the more highly absorbent and at high temperatures more powerfully radiant carbon dioxide or water-vapor. Since, at high temperatures and in thin layers, the radiative power of these strong absorbents is immensely greater than that of air, it follows that the rate of radiant increase with the depth for air at higher temperatures must be very much slower than for carbon dioxide, and that at particular depths and temperatures, which have been reached in the present research, the total radiations of these substances are more nearly equal. It is not possible, however, that equable increase of air radiation with depth can continue indefinitely, since the heat lost by layers of such dimensions as we have in the atmosphere, and imparted by radiation from the atmosphere to the earth, would have to be much greater, in that case, than it actually is.

The differential deflections in Tables 30 and 31 may best be compared by stating them as percentages of the deflection with disk at 4 feet.

TABLE 40.

Position of disk.	Depth of gas.	Air at 185°.5 and 723 mm.	CO_2 at 125°.8 and 766 mm.	Increase per foot.	
				Air.	CO_2.
Feet.	*cm.*				
0.35	0	0	0	....	....
1.0	19.8	18.4	33.3	28.3	51.2
2.0	50.3	48.5	72.0	30.1	38.7
3.0	80.8	73.6	98.7	25.1	26.7
4.0	111.3	100.0	100.0	26.4	1.3
5.0	141.8	98.2	97.1	....	....

The slight decrease in the differential deflection at the fifth foot, as compared with that at the third or fourth foot in the experiments with carbon dioxide, is possibly due to the chilling of the radiating disk in the extreme end position, or to absorption of disk radiation by CO_2, a point which will be examined farther on; but the change in the air series at the fifth foot is presumably to be attributed to a different cause. The observations of Table 30 were the first made with apparatus *C*. Intermediate positions were reached by stopping the rod which carries the disk at successive marks, but the end reading was secured by pulling out the disk until its clamp was felt or heard to strike against the end-plate. The supports of the cylinder were not stiff enough to resist the shock, and the entire mass of iron moved to and fro though a sufficient range to produce a deflection of a few divisions on the galvanometer by magnetic influence. Suspecting such an effect, which was, however, irregular, and one for which no correction can be applied, I had the supports stiffened by braces, and the remedy proved effectual. The error only affects the readings

on the fifth foot in Table 30, and these have been rejected. Observations made after the insertion of the braces, and with a cold cylinder, to see if any magnetic effect was exerted by the motion of the steel rod, gave a deflection of -0.29 div. for the outward motion of 4.65 feet. As this is included in possible errors of observation, no correction is applied for magnetic influence.

The relative increments of radiation, given in the last column of Table 40, demonstrate that a layer of carbon dioxide, 3 feet deep, is sufficient to extinguish by its absorption practically all the radiation of the peculiar quality emitted by this gas; and thus that no further increase in the depth of the radiating layer is of avail for adding to the emission of the only rays which this substance is capable of sending forth. If this is a general law, the brilliancy of a glowing gaseous mass (a solar prominence, for instance) depends, after a certain depth has been exceeded, entirely upon the temperature, but not on the dimensions of the layer; and the cooling of a gaseous mass of great depth depends on the radiation of a comparatively shallow layer whose locus travels inward. It might be inferred from the preceding experiments that layers of air and of carbon dioxide, 1 foot deep, and at atmospheric pressure, radiate equally near the temperature of boiling water to an inclosure near the freezing point; but these results require the application of further corrections before the final quantitative values can be stated.

RADIATION FROM MULTIPLE FLAMES.

In order to examine the effect of increasing depth on the radiation of a gas at high temperature, a series of five Bunsen burners, with apertures 2.5 by 0.2 inches, giving flat flames, were arranged so that the flames were presented broadside to the line of sight. Only so much of the

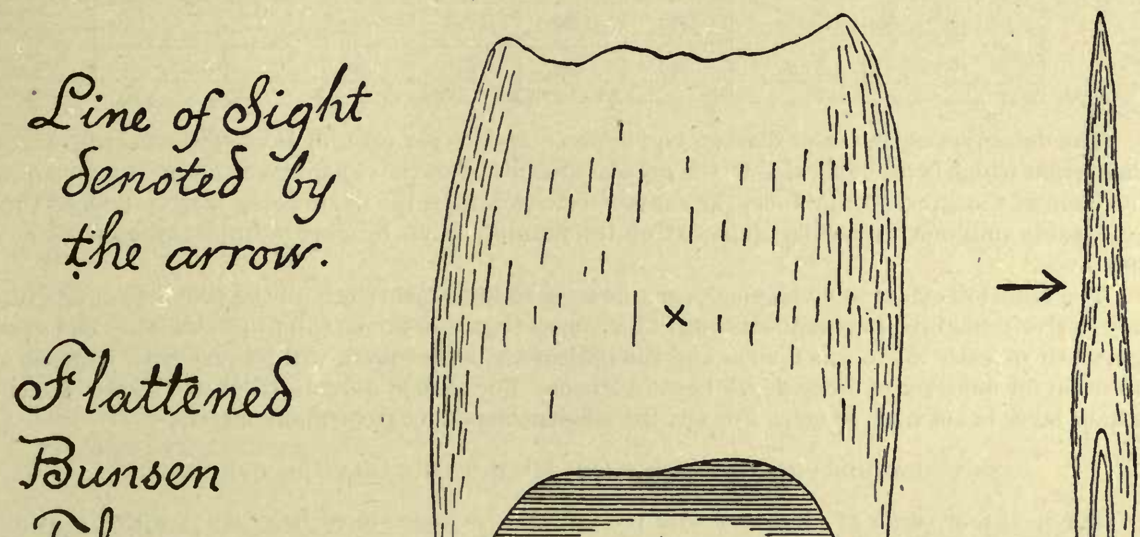


Fig. 8

flame as could be seen through the narrow aperture of the multiple tin-plate screen was permitted to radiate to the bolometer. The most distant flame was 2 feet from the bolometer; the nearest, $1\frac{1}{2}$ feet. Exposures were made by withdrawing a blackened copper screen containing cold water. The shape of the flame is shown, full size, in fig. 8.

November 15, 1895.

Temperature of room, 14°.8 C. Dew-point 7°.8 C., corresponding to a pressure of aqueous vapor of 7.88 mm., or 8.11 grams per cubic meter, and to an equivalent liquid depth of 0.000 371 cm. in the distance to the nearest flame, and 0.000 494 cm. in the path to the most distant flame.

Battery galvanometer, 100 div.

Shunt = 0.1451. Multiplier = 6.89. Temperature of cold screen, 10° to 18° C.

TABLE 41.

Number of flames.	5	4	3	2	1 (most distant)	1 (nearest)
Depth of flame.	3.0 cm.	2.4 cm.	1.8 cm.	1.2 cm.	0.6 cm.	0.6 cm.
Deflections (Shunted galvanometer)	244.5	217.5	175.5	128.5	69	74
	245	218	176	129	70.5	72
	250.5	219	176	129.5	66.5	73
	252	221.5	174.5	128.5	69	73
	245.5	220.5	177	130	70	73.5
	249	216	177	125	69.5	75.5
	251.5	218	174.5	129.5	66.5	77.5
	250.5	220	173	130.5	71	73
	252.5	214	172.5	126	69	72
	250	220.5	177	130	71.5	72.5
Mean (shunted)	249.1	218.5	175.3	128.7	69.3	73.6
" (unshunted)	1723	1506	1208	887	478	507
Change per 0.6 cm.	217	298	321	395	493	

The deflection on the most distant single flame is 94.2 per cent. of that on the nearest one, a diminution which is probably due to the greater amount of water-vapor traversed by the rays from the flame at the greatest distance, the radiant emission from the flame being largely that of very hot steam, and one especially depleted of its peculiar rays by even a thin layer of its own substance.

The addition of successive flames, each new one radiating through all the previous ones, gives progressively diminishing increments of radiation, as shown in the last line of Table 41. The average depth of each flame was 6 mm., and the indication is that there will be very little increase of radiation for addition of flame-depth beyond 20 cm. For carbon dioxide, the depth of the efficient radiant layer is not over 90 cm. For air, the efficient depth must be many meters.

CONTINUATION OF MEASURES MADE WITH THE RADIATION CYLINDER.

The next four series of measures with the radiation cylinder have been made with a continuously rising temperature. Hence, according to the general theory of the apparatus, the recorded thermometer readings are lower than the true mean temperatures of the air within the cylinder, by amounts which can perhaps be estimated later; but since all of these series have been taken on a common plan, and the rapidity of heating has been nearly the same, the results are comparable.

The curves of heating are given in fig. 9, abscissæ being intervals from the commencement of heating and ordinates being recorded cylinder temperatures.

The rate of heating is a trifle slower for rarified air. Otherwise, the heating curves are similar. The throw of the disk was to its full extent in every case, the radiant depth being 141.8 cm. Deflections were observed in groups of five every six minutes. Only the mean readings are given here.

February 9, 1893.

Cylinder containing air at normal pressure, 737 mm., and nearly dry, but not purified from carbon dioxide.

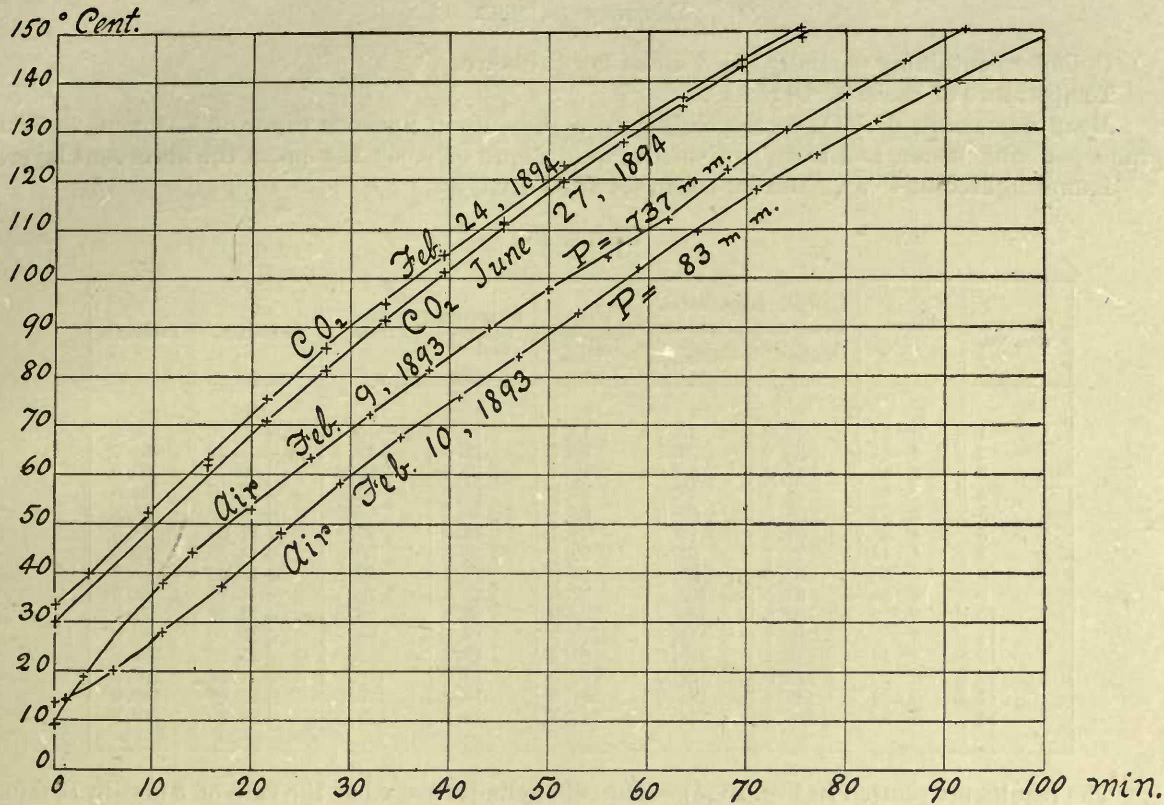


Fig. 9

Temperature of room, at $3^h\ 0^m$, 11°.1 C.; at $3^h\ 30^m$, 12°.2; at $4^h\ 0^m$, 13°.3; at $4^h\ 30^m$, 14°.4; at $5^h\ 0^m$, 15°.5.

Mean dew-point, 4°.4 C., corresponding to a pressure of aqueous vapor of 6.24 mm. or 6.50 grams per cubic meter, and to an equivalent liquid depth of 0.000 244 cm. in the absorbent layer.

Lamps lighted at $3^h\ 20^m$. Burner cocks set at 35 div.

The results are platted in fig. 10 (*a*).

Abscissæ = temperature-excesses (uncorrected).

Ordinates = deflections.

TABLE 42.

Observation No.	Time.	Cylinder temperature.		Mean temperature.	Bolometer temperature.	Excess.	Deflection.	Pressure.
		Before.	After.					
	h. m.	°	°	°	°	°	div.	mm.
1	3 8	9.3	....	9.3	16.4	— 7.1	— 0.85	737
2	3 37	43.9	53.2	48.6	17.5	+31.1	+ 8.50	
3	3 43	53.2	63.3	58.3	17.7	40.6	+ 9.21	
4	3 49	63.3	72.1	67.7	17.9	49.8	+11.88	
5	3 55	72.1	81.4	76.8	18.1	58.7	+11.05	
6	4 1	81.4	89.9	85.7	18.3	67.4	+12.78	
7	4 7	89.9	98.0	94.0	18.6	75.4	+12.33	
8	4 13	98.0	104.4	101.2	18.8	82.4	+14.70	
9	4 19	104.4	114.2	109.3	19.0	90.3	+15.87	
10	4 25	114.2	122.1	118.2	19.2	99.0	+16.06	
11	4 31	122.1	130.0	126.1	19.4	106.7	+19.29	
12	4 37	130.0	137.2	133.6	19.7	113.9	+21.66	
13	4 43	137.2	144.0	140.6	19.9	120.7	+22.64	
14	4 49	144.0	150.3	147.2	20.1	127.1	+22.48	

February 10, 1893.

Cylinder containing partially dried air at low pressure.

Temperature of room, 13°.8 to 14°.8 C.

Mean dew-point, 6°.7 C., corresponding to a pressure of aqueous vapor of 7.31 mm., or 7.56 grams per cubic meter, and to an equivalent liquid depth of 0.000 284 cm. in the absorbent layer.

Lamps lighted at $4^h\ 0^m$. Burner-cocks set at 35 div.

TABLE 43.

Observation No.	Time.	Cylinder temperature.		Mean temperature.	Bolometer temperature.	Excess.	Deflection.	Pressure.
		Before.	After.					
	h. m.	°	°	°	°	°	div.	mm.
1	3 51	13.6	13.7	13.7	18.8	− 5.1	+ 0.26	58.5
2	4 14	28.0	37.1	32.6	19.0	+13.6	+ 3.91	56.7
3	4 20	37.1	48.2	42.7	19.1	23.6	+ 6.73	60.0
4	4 26	48.2	58.2	53.2	19.2	34.0	+ 8.16	64.3
5	4 32	58.2	67.6	62.9	19.2	43.7	+ 8.38	68.5
6	4 38	67.6	75.7	71.7	19.3	52.4	+11.69	72.3
7	4 44	75.7	84.0	79.9	19.3	60.6	+11.09	76.8
8	4 50	84.0	93.0	88.5	19.4	69.1	+12.26	81.8
9	4 56	93.0	102.2	97.6	19.5	78.1	+14.78	86.5
10	5 2	102.2	109.7	106.0	19.5	86.5	+13.99	91.5
11	5 8	109.7	118.1	113.9	19.6	94.3	+15.60	96.5
12	5 14	118.1	125.0	121.6	19.6	102.0	+17.22	101.8
13	5 20	125.0	131.6	128.3	19.7	108.6	+21.43	106.3
14	5 26	131.6	137.9	134.8	19.8	115.0	+22.07	110.8
15	5 32	137.9	144.2	141.1	19.8	121.3	+23.39	116.8

The results are plotted in Fig. 10 (*b*). The cold cylinder leaked at the rate of 5 mm. in 15 min. at the lower pressures. Computing the proportional leakage for three intervals in the above series, and comparing the observed pressures, corrected for the expansion of air by heat, we have:

	mm.
$4^h\ 14^m$ to $4^h\ 44^m$, change of pressure,	56.7 to 76.8
By thermal change, $56.7 \times [1 + (60.6 - 13.6) \times .00367] =$	66.5
Observed leakage,	10.3
Leakage, computed for 30 min. interval,	10.0
Residual,	+0.3
$4^h\ 44^m$ to $5^h\ 8^m$, change of pressure,	76.8 to 96.5
By thermal change, $76.8 \times [1 + (94.3 - 60.6) \times .00367] =$	86.3
Observed leakage,	10.2
Leakage, computed for 24 min. interval,	8.0
Residual,	+2.2
$5^h\ 8^m$ to $5^h\ 32^m$, change of pressure,	96.5 to 116.8
By thermal change, $96.5 \times [1 + (121.3 - 94.3) \times .00367] =$	106.0
Observed leakage,	10.8
Leakage, computed for 24 min. interval,	8.0
Residual,	+2.8

The excess of observed pressure over computed at the higher temperatures is probably to be attributed to the real mean temperature being higher than that assumed from thermometer readings in heating, as explained in the general theory of the apparatus; but it is possible that the leaks may have increased in the course of the process of heating. Leaks in the luting had been started by the previous day's heating and the joints had to be tightened at the beginning of the observations of February 10. Another possible cause of the discrepancy is that some vapor may have been evolved by the heat at the highest temperatures; but in this case some special fluctuation of the readings of the galvanometer might be anticipated, and of this there is no sign.

February 24, 1894.

Cylinder filled with dry carbon dioxide at atmospheric pressure, 748 mm.

Temperature of room, 12°.8 C. at 2^h 10^m, to 15°.1 C. at 3^h 47^m.

Dew-point, 1°.4 C., corresponding to a pressure of aqueous vapor of 5.05 mm., or 5.32 grams per cubic meter, and 0.000 190 cm. of liquid water in the absorbent air layer.

Lamps lighted at 2^h 19^m. Cocks 35 div.

TABLE 44.

Observation No.	Time.		Cylinder temperature.		Mean temperature.	Bolometer temperature.	Excess.	Deflection.	Pressure.
			Before.	After.					
	h.	m.	°	°	°	°	°	div.	mm.
1	2	26	39.8	52.2	46.0	18.2	27.8	+ 3.20	748
2	2	32	52.2	63.0	57.6	18.4	39.2	+ 4.78	
3	2	38	63.0	75.3	69.2	18.5	50.7	+ 4.51	
4	2	44	75.3	85.8	80.6	18.7	61.9	+ 7.63	
5	2	50	85.8	94.8	90.3	18.8	71.5	+ 8.53	
6	2	56	94.8	104.8	99.8	19.0	80.8	+10.73	
7	3	2	104.8	111.5	108.2	19.1	89.1	+ 8.10	
8	3	8	111.5	122.8	117.2	19.3	97.9	+10.80	
9	3	14	122.8	130.8	126.8	19.4	107.4	+12.92	
10	3	20	130.8	136.8	133.8	19.6	114.2	+13.49	
11	3	26	136.8	144.1	140.5	19.7	120.8	+13.45	
12	3	32	144.1	150.6	147.4	19.9	127.5	+15.80	

The results are platted in fig. 10 (*c*).

June 27, 1894.

Cylinder containing dry carbon dioxide at atmospheric pressure, 730 mm. (at 0° C.).

Temperature of room, 29°.4 C., with a rise of one-half degree per hour.

Dew-point, 15°.0 C., corresponding to a pressure of aqueous vapor of 12.67 mm., or 12.71 grams per cubic meter, and to an equivalent liquid depth of 0.000 478 cm. in the absorbent layer of air.

Lamps lighted at 3^h 32^m. Burner cocks at 40 div.

TABLE 45.

Observation No.	Time.		Cylinder temperature.		Mean temperature.	Bolometer temperature.	Excess.	Deflection.	Pressure.
			Before.	After.					
	h.	m.	°	°	°	°	°	div.	mm.
1	3	51	61.6	70.9	66.3	34.2	32.1	+ 5.59	730
2	3	57	70.9	81.2	76.1	34.2	41.9	+ 6.64	
3	4	3	81.2	91.2	86.2	34.3	51.9	+ 6.34	
4	4	9	91.2	101.2	96.2	34.3	61.9	+ 8.16	
5	4	15	101.2	111.0	106.1	34.4	71.7	+ 9.50	
6	4	21	111.0	119.6	115.3	34.4	80.9	+ 9.38	
7	4	27	119.6	127.6	123.6	34.5	89.1	+10.58	
8	4	33	127.6	134.8	131.2	34.5	96.7	+10.28	
9	4	39	134.8	142.9	138.9	34.6	104.3	+ 9.72	
10	4	45	142.9	148 6	145.8	34.6	111.2	+11.73	
11	4	51	148.6	154.2	151.4	34.7	116.7	+12.69	

The results are platted in fig. 10 (*d*). Fig. 10 (*a*) gives for air a radiation of 24 div. at excess 130° C., or 0.185 div. per degree; and fig. 10 (*b*) gives 24 div. for 125° excess, or 0.192 div. per degree, no appreciable change being produced by rarefaction. Fig. 10 (*c*) gives for carbon dioxide a radiation of 14 div. for an excess of 120° C., or 0.117 div. per degree; and fig. 10 (*d*) gives 14 div.

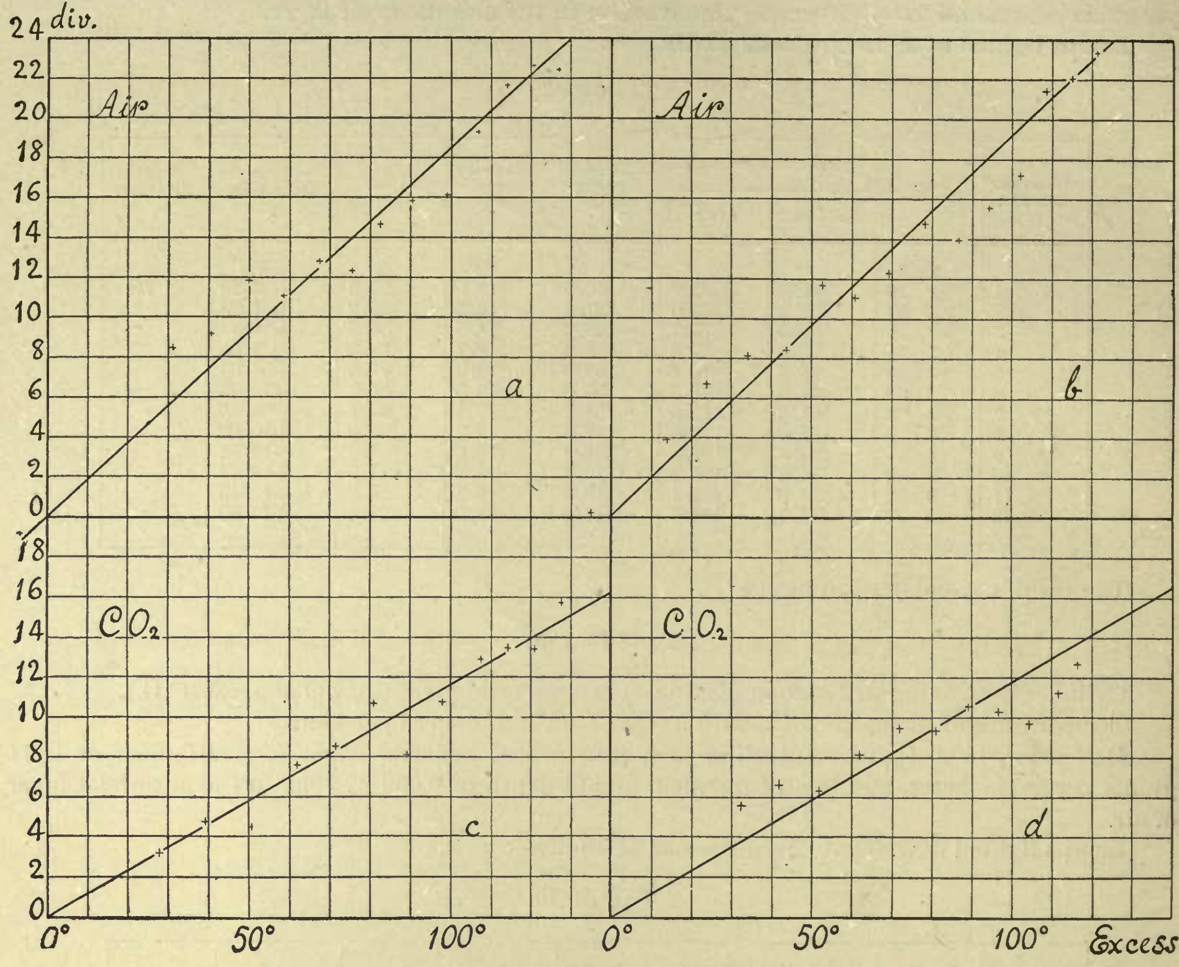


Fig. 10

for 118°, or 0.119 div. per degree, both observations being at atmospheric pressure. Reducing this deflection to the galvanometer constant of 1893, it becomes 0.1254 div., and the ratio of radiations (141.8 cm. layer) is:

$$\text{Air} : CO_2. \quad . \quad . \quad . \quad . \quad \frac{0.1885}{0.1254} = 1.50.$$

This ratio is, of course, only applicable to the limited range of depth and temperature from which it has been obtained. The increase of water in the absorbent layer, in the ratio $\frac{478}{190} = 2.52$, has not affected the radiation of carbon dioxide. The bands of these substances, in the infra-red, overlap to some extent, but if composed of fine lines, they need not interfere.

GASEOUS RADIATION WITH A COOLING CYLINDER (LAMPS EXTINGUISHED).

The next experiments, conducted with a cooling cylinder, should give trustworthy values according to the general theory of the apparatus.

June 28, 1894.

Cylinder filled with dry carbon dioxide.

Temperature of room, 30°.4 C.; of bolometer, 35°.4.

Mean dew-point, 15.°2 C., corresponding to a pressure of aqueous vapor of 12.84 mm., or 12.87 grams per cubic meter, and to a liquid depth of 0.000 484 cm. in the absorbent layer of air.

The measures were to be made near normal pressure, and at points marked with an asterisk, a little carbon dioxide was allowed to flow into the cylinder to restore the pressure. Each deflection in the following table is the mean of five. The first reading in each series corresponds to the maximum temperature and is abnormal:

TABLE 46.

Series 1.

Time.	Cylinder temperature. Before.	Cylinder temperature. After.	Mean temperature.	Excess.	Cooling rate per minute.	Deflection.	Pressure at 0° C.
h. m.	°	°	°	°	°	*div.*	*mm.*
2 8							744
2 11.5	133.2	132.8	133.0	97.6	0.13	+15.68	
2 15	132.8	129.9	131.4	96.0	0.73	+12.44	
2 17							731
2 21.3	126.7	124.3	125.5	90.1	1.10	+ 8.71	
*2 23							718
2 29							751
2 32	117.0	112.4	114.7	79.3	0.81	+ 6.32	
2 35							742
2 37	112.4	109.0	110.7	75.3	0.67	+ 4.65	
2 39							737
2 47	105.1	103.8	104.5	69.1	0.48	+ 3.86	
2 48							726

Series 2.

Time.	Cylinder temperature. Before.	Cylinder temperature. After.	Mean temperature.	Excess.	Cooling rate per minute.	Deflection.	Pressure at 0° C.
h. m.	°	°	°	°	°	*div.*	*mm.*
3 43							741
3 45.5	136.2	134.4	135.3	99.9	0.36	+14.51	
3 48							734
3 55							728
3 56.5	128.7	125.0	126.9	91.5	1.23	+ 9.52	
3 58							715
3 59.5	125.0	119.9	122.5	87.1	1.70	+ 8.21	
*4 1							706
4 14							741
4 16.5	113.0	109.4	111.2	75.8	0.72	+ 5.66	
4 19							739
4 21	109.4	105.2	107.3	71.9	1.05	+ 4.55	
4 23							733
4 25	105.2	101.7	103.5	68.1	0.88	+ 4.09	
4 27							729

The mean of the observed pressures in the first series is 736 mm.; in the second 730 mm.; and the mean cooling rate is 0°.80 per minute.

On this date a final series was taken with carbon dioxide as the radiant, to see if any effect could be noted from varying the pressure while the temperature remained constant or was cooling very slowly.

TABLE 47.

Temperature.	Excess.	Cooling per minute.	Deflection.	Pressure.
°	°	°	*div.*	*mm.*
134.8	99.4	0.53	+10.09	739
135.0	99.6	0.00	+11.43	588
135.4	100.0	0.40	+11.19	401
134.5	99.1	0.20	+12.74	208
133.8	98.4	0.08	+12.35	213

Here a slight increase of the deflection was observed when the pressure diminished.

The next experiments were made with air purified from both aqueous vapor and carbon dioxide. The air entered the apparatus through a series of flasks and tubes. First came two flasks (1 and 2) containing porous chloride of calcium; then (3) a long horizontal tube filled with crushed and chemically pure hydrate of sodium, the stoppers being protected by asbestos. Next (4) came a flask filled with a solution of sodium hydrate in glycerin, through which the air passed in bubbles whose rate of flow could be regulated by the graduated stopcock. After this came (5) another flask of porous chloride of calcium, and last (6 and 7) two flasks containing flocculent phosphoric anhydride. (1) and (2) protect the sodium hydrate from atmospheric moisture; (4) is relied on to absorb the last traces of carbon dioxide. The water coming from the chemical reaction

$$2\,NaOH + CO_2 = Na_2CO_3 + H_2O,$$

is absorbed by (5), (6), and (7).

Finally a bowl of phosphoric anhydride and, in the last experiment, pure sodium were introduced directly into the radiation cylinder to absorb the small amount of impurity coming from leakage.

The leakage being proportionally very much greater at low pressures, after a preliminary exhaustion and filling, the pressure was kept about 50 mm. below the normal for a long time, the outer air flowing slowly through the flasks and completing the purification by successive dilutions.

August 15, 1895.

Pressure, 731 mm. at 0° C.

Temperature of room, 31°.3 C.; of bolometer, 36°.3.

Dew-point, 6°.7 C. Pressure of aqueous vapor, 7.31 mm., or 7.56 grams per cubic meter, equivalent to a liquid depth of 0.000 284 cm. in the absorbent layer. Disk of blackened asbestos.

Temperature in (1) cooling from 100°.0 to 96°.4. Excess 61°.9
" " (2) " " 91 .5 " 89 .3 " 54 .1
" " (3) " " 81 .0 " 79 .0 " 43 .7

Deflections:	(1)	(2)	(3)
	div.	div.	div.
	+13.8	+7.2	+6.6
	13.9	8.4	4.2
	14.0	6.1	4.3
	11.7	8.3	4.7
	11.3	8.3	3.1
Mean deflections:	+12.94	+7.66	+4.58

August 17, 1895.

Pressure, 728 mm.

Temperature of room, 29°.9 C.; of bolometer, 34°.9.

Dew-point, 14°.4. Pressure of aqueous vapor, 12.19 mm., or 12.26 grams per cubic meter, equivalent to a liquid depth of 0.000 461 cm. in the absorbent layer. Disk of blackened asbestos.

Temperature in (1) cooling from 92°.0 to 90°.9. Excess 56°.6.
" " (2) " " 79 .5 " 77 .2 " 43 .5
" " (3) " " 69 .4 " 68 .0 " 33 .8
" " (4) " " 60 .0 " 58 .8 " 24 .5

Deflections:	(1)	(2)	(3)	(4)
	div.	div.	div.	div.
	5.5	3.7	3.0	2.7
	7.2	4.0	3.2	2.9
	6.6	5.8	2.0	3.1
	7.8	3.8	1.3	2.2
	8.0	4.1	1.0	2.5
Mean deflections:	+7.02	+4.28	+2.10	+2.68

August 21, 1895.

Pressure, 735 mm.

Temperature of room, 25° C.; of bolometer, 30°.

Dew-point, 4°.7 C. Pressure of aqueous vapor, 6.37 mm., or 6.63 grams per cubic meter, equivalent to a liquid depth of 0.000 249 cm. in the absorbent layer.

Temperature in (1)	cooling from	105°.9	to	105°.0.	Excess	75°.5
" " (2)	" "	100 .0	"	96 .7	"	68 .4
" " (3)	" "	89 .5	"	86 .6	"	58 .1
" " (4)	" "	80 .2	"	77 .2	"	48 .7

Deflections:	(1)	(2)	(3)	(4)
	div.	div.	div.	div.
	6.0	7.6	2.6	1.6
	7.4	5.5	3.0	1.1
	9.5	6.4	2.0	2.8
	8.9	5.7	2.1	0.7
	9.3	5.6	4.6	0.8
Mean deflections:	+8.22	+6.16	+2.86	+1.40

August 22, 1895.

Pressure, 738 mm.

Temperature of room, 27° C.; of bolometer, 32°.

Dew-point, 7°.8 C. Pressure of aqueous vapor, 7.88 mm., or 8.11 grams per cubic meter, equivalent to a liquid depth of 0.000 305 cm. in the absorbing layer.

Temperature in (1)	constant at			71°.0.	Excess	39°.0
" " (2)	" "			71 .0	"	39 .0
" " (3)	cooling from	71°.0	to	70 .5	"	38 .8
" " (4)	" "	70 .5	"	69 .4	"	38 .0
" " (5)	" "	69 .4	"	69 .0	"	37 .2

Deflections:	(1)	(2)	(3)	(4)	(5)
	div.	div.	div.	div.	div.
	11.6	6.8	5.3	3.0	2.3
	8.0	5.4	4.8	5.6	3.9
	7.0	6.6	4.2	3.4	2.0
	5.0	6.1	5.6	4.4	3.4
	5.9	4.1	3.3	3.3	2.4
Mean deflections:	+7.50	+5.80	+4.64	+3.94	+2.80

The radiation cylinder on this occasion had been heated for a long time by the two central burners only. The horizontal inequality of temperature produced by the uneven heating persisted until the end of this series. The last reading is nearly normal.

Finally the radiation cylinder was kept at a nearly constant temperature—not far from 100° C.—for a week, the air being in contact with metallic sodium. The following readings were taken during the interval:

September 13, 1895.

Pressure, 733 mm.

Temperature of room, 26° C.; of bolometer, 31°.

Dew-point, 12°.2 C. Water-vapor pressure, 10.57 mm., or 10.71 grams per cubic meter. Equivalent liquid depth in absorbing layer, 0.000 403 cm.

Temperature, 100°.0 C. (steady). Excess, 69°.0.

Deflections: 7.3, 6.3, 8.0, 7.8, 8.2; mean, + 7.52 div.

September 14, 1895.

Pressure, 737 mm.

Temperature of room, 23°.5 C.; of bolometer, 28°.5.

Dew-point, 9°.4 C. Pressure of aqueous vapor, 8.78 mm., or 8.98 grams per cubic meter. Equivalent liquid depth in the absorbent layer, 0.000 338 cm.

Temperature, 97°.8 C. (steady). Excess, 69°.3.

Deflections: 7.0, 8.4, 7.7, 7.0, 4.5; mean, + 6.92 div.

September 19, 1895.

Pressure, 733 mm.

Temperature of room, 28°.8 C.; of bolometer, 33°.8.

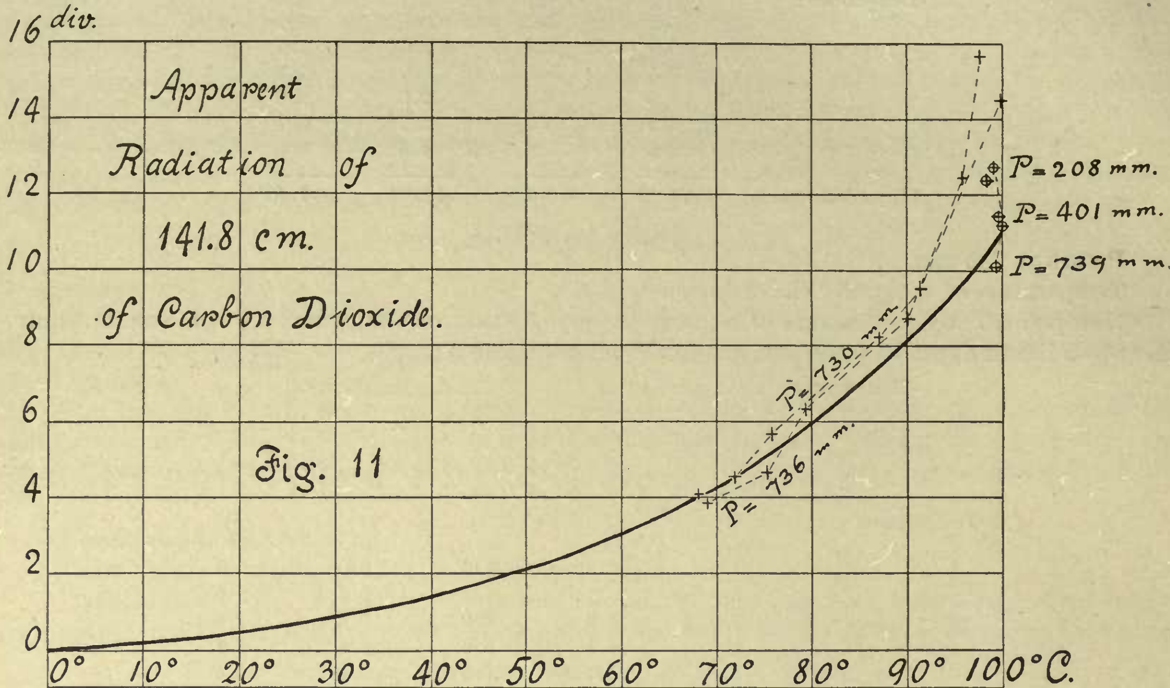
Dew-point, 17°.8 C. Pressure of aqueous vapor, 15.14 mm., or 15.04 grams per cubic meter. Equivalent liquid depth in the absorbent layer, 0.000 566 cm.

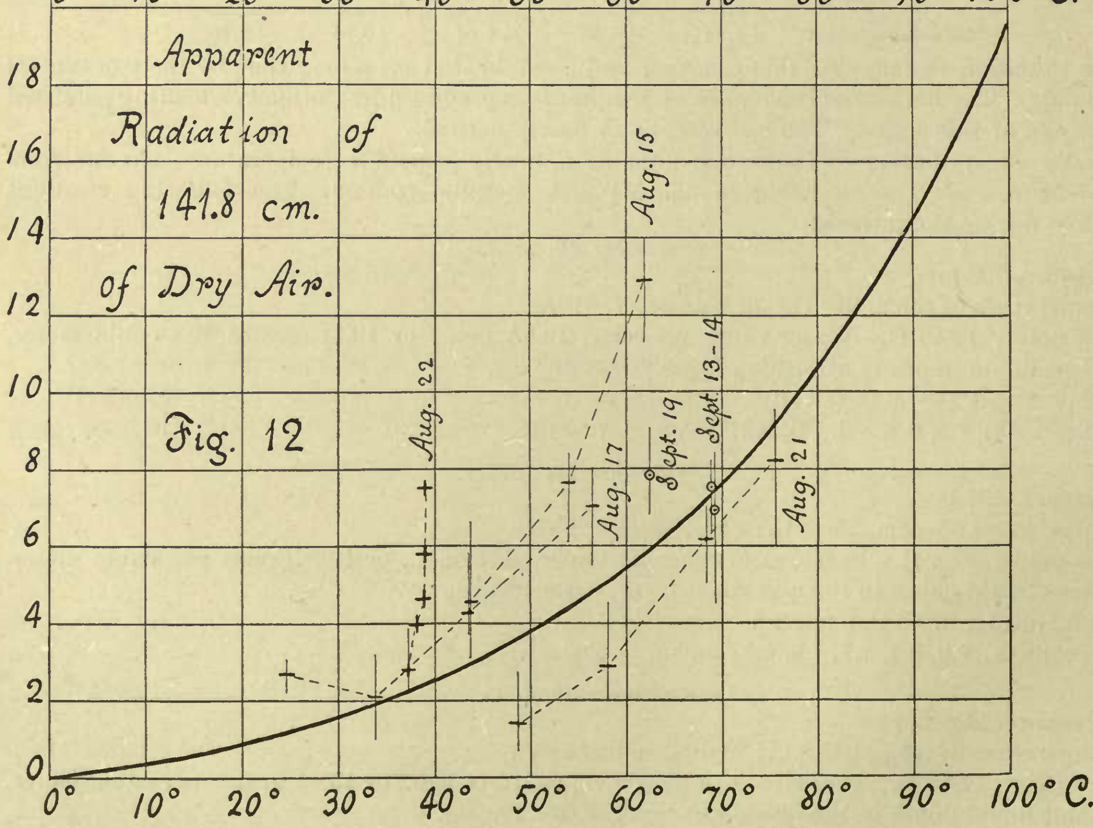
Temperature, 96°.2 C. (steady). Excess, 62°.4.

Deflections: 8.9, 7.1, 7.2, 9.1, 6.8; mean, +7.82 div.

FINAL CURVES OF APPARENT RADIATION BY METHOD C.

Rejecting the first members of each series, because they are vitiated by inequalities of temperature, the remaining deflections with carbon dioxide on June 28, 1894 (Table 46), form a





single consistent series, representing the maximum apparent radiation from this gas, so far as radiation depends upon depth, which deserves exceptional weight (fig. 11). Passing a mean curve

through these points and those of Table 47, and multiplying the ordinates by the ratio 1.5, already obtained for air radiation from a layer 141.8 cm. deep, as compared with the radiation of a like layer of carbon dioxide, and reducing to like instrumental conditions, a curve is obtained (fig. 12) which represents, as well as any which I can devise, the considerable range in air values which have been obtained between August 15 and September 19, 1895. The curve falls between the observations of August 17 and August 21, passes between the records of radiation at stationary temperature of September 13 and 14, although considerably below the stationary point of September 19, and is sufficiently below the obviously abnormal curve of August 22 to be free from the suspicion of being affected by any remaining inequality of temperature. The readings of August 21 are a little too small, the rock-salt plate having a deposit of dust on its surface. The observations of August 15 have not progressed far enough to be entirely uninfluenced by inequality of temperature. Even the deflections at stationary temperature may be a little too large on this account, and the curve should pass below them rather than through them. In plotting these variant air values lines have been drawn through the mean positions, showing the extreme range in the deflections (fig. 12).

The observations of carbon dioxide radiation were made in 1894, those of air in 1895. Consequently the ordinates for the curve in fig. 12, obtained by multiplying those of fig. 11 by 1.5, have been further multiplied by the ratio of the galvanometer constants in those years, which, by p. 26, is $\frac{438}{368} = 1.19$, giving with the condition of instruments in 1895 these values for air radiation:

Excess:	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°
Deflection:	0.38	0.86	1.54	2.50	3.78	5.46	7.60	10.59	14.52	19.64

Reduced with the galvanometer constant of 1894, the following table is obtained, giving the adopted apparent radiations of a 141.8 cm. layer for every tenth degree of temperature-excess from 0 to 100°, as read from the smooth curves, the values being expressed finally in absolute units, or radims $\times (10)^{-9}$

TABLE 48.

Temperature excess.	10°.	20°.	30°.	40°.	50°.	60°.	70°.	80°.	90°.	100°.
	div.	*div.*	*div.*	*div.*	*div.*	*div.*	*div.*	*div.*	*div.*	*div.*
CO_2	0.21	0.48	0.86	1.40	2.12	3.06	4.26	5.93	8.13	11.00
Air	0.32	0.72	1.29	2.10	3.18	4.59	6.39	8.90	12.20	16.50
CO_2*	9	21	38	61	93	134	187	260	356	482
Air	14	32	57	92	139	201	280	390	534	723

* Radiation in ninth-radims.

The measured gaseous radiations are somewhat too small, because the gaseous absorption of disk radiation has been greater with the disk out, thus diminishing the deflection, and because the rock-salt and the absorbent layer of air have kept back a part of the radiation of the hot gas.

By Method B (*ante*, p. 44), the radiation of 1 meter of *moist* air is about 0. 000 000 104 radim at 40° excess.

By Method C, the radiation of *dry* air, reduced to the same depth, is 0. 000 000 065 radim at 40° excess.

Both radiations have been diminished by absorption. In particular, the result by Method C requires an increase of about one-third on account of the absorption by the rock-salt plate. The hot moist air might be expected to radiate more powerfully than dry air at the same temperature, and the remaining difference is probably attributable to this qualitative distinction.

Although the affinity of rock-salt for moisture made the result of the experiment somewhat problematical, I decided to try to measure the radiation of water-vapor by Method C, allowing steam to run into the hot and partially exhausted cylinder. I had supposed at the time of making this experiment that the gradual introduction of steam into a *hot* partially exhausted vessel would not be attended by liquid condensation. The result proved that the flow of steam was too rapid,

and that the cylinder should have been full of air at the start, the air-pumps being used merely to keep the pressure from rising much above normal. Hirn, in 1862, had found that the sudden diminution of pressure in steam at 152° C. and 5 atmospheres pressure, gave a cloudy condensation, but this result was unknown to me until I read it in Preston's *Theory of Heat*, published about the time of my observations. I regret that the simple expedient of allowing air to remain in the cylinder while the steam was entering did not occur to me until after the apparatus was dismounted.

EXPERIMENT ON THE RADIATION OF STEAM.

Temperature of room, 33° C.; of bolometer, 38°.

Dew-point, 3°.1 C.; pressure of aqueous vapor 5.70 mm., or 5.96 grams per cubic meter. Equivalent liquid in the absorbent layer = 0. 000 224 cm. After exhaustion to 79 mm. the mean temperature of the radiation cylinder was 132°, cooling at the rate of 1°.5 per minute, and the mean deflection from air, at 99° excess, was + 13.02 div. The heater, containing boiling water, was then connected until the pressure reached 731 mm., the temperature meantime rising to 142°, or to an excess of 104°. A mean deflection of + 5.20 div. was then obtained, followed by another of + 4.84 div., excess 101°. Within 15 minutes after these readings, the pumps having been worked, the pressure had diminished to 126 mm., temperature 135°, excess 97°. The mean deflection had increased to + 25.62 div., the temperature being nearly stationary.

Undoubtedly, the watery condensation at first precipitated a film of moisture, or dew, on the rock-salt, which diminished the deflection by its irregular scattering of the rays; but when the pressure was removed, this film evaporated, and even through the now corroded rock-salt plate, which transmitted scarcely more than two-thirds of the radiation, this deflection of 25.6 div. was measured. I infer that with a clear plate, something like 38 div., or about 70 per cent. of the radiation of lampblack at a like excess, might be obtained from a layer of steam, at 126 mm. pressure, 142 cm. deep. Under these circumstances, and within the range of my observations, water-vapor (with no allowance for absorption by the vapor in the air of the room), radiates about three times as powerfully as air. In small amount, however, water-vapor radiates much more than the simple proportion of the quantities would indicate.

EXPLANATION OF RESULTS AT LOW PRESSURES.

I have alluded (*ante*, p. 54) to the small difference between deflections at ordinary and at low pressures as being at first sight surprising; but the explanation is simple enough. According to Dulong and Petit (*Ann. de Chimie et de phys.* (2), tome 7, p. 337, 1817), convection in air at 720 mm. pressure removes from a hot body 2.548 times as much heat as at 90 mm. pressure; but since the mass of unit volume is eight times as great at the higher pressure, the air heated by convection at the lower pressure, (1) if equal volumes are set in motion, must get $\frac{8}{2.548} = 3.139$ times as hot; or else, (2) if the air gets no hotter, 3.139 times as large a volume of low-pressure air must move in the convection current in the same interval of time.

Under identical thermal conditions, the radiation cylinder being heated by four large Bunsen burners, with stop-cocks set at 35 div., air, first at 737 mm. and second at 83 mm. pressure, was heated to the same extent (80° C.) in one hour, with little difference in the radiation from the heated air column. The final temperature of the entire body of mixed air may be nearly the same in either case, but the radiation through the limited aperture should be greater in the first condition, because radiation increases more rapidly than temperature, and the smaller volume of superheated low-pressure air should have the greater radiant efficiency. The true rate of increase of gaseous radiation with rise of temperature, as will be eventually shown, is such that if the temperature is three times as great, the radiation is increased in something like the ratio of eight to one. Hence if the volume of rarefied air has one-eighth the mass, and is three times as hot as the same volume of high-pressure air, the radiation per unit of mass (condition 1) will be eight times as great for the air of smaller density, or identical per unit of volume for either high or low pressure. The actual rate of heating depends on that of the iron cylinder, and not on the thermal capacity of the air, whose mass is relatively insignificant. The result of the measurements of

gaseous radiation implies that the volume of air set in motion in the unit of time by convection is independent of the pressure, but that the temperature of this volume is such that the radiant effect of unit mass increases in inverse proportion to the mass of unit volume. The argument also implies that, at the same temperature, the radiant effect is proportional to the mass of the radiating gas, and is independent of the volume which this mass may occupy, always with the provision that the mass is a small one, or not great enough for the self-absorbent action of the gas on its own radiations to produce any essential modification of the radiant power.

Since the heating of the bottom of the iron cylinder by the flames was far from uniform, it is evident, as has been demonstrated already in other ways, that the measured radiation does not proceed uniformly from the entire mass of air in range with the bolometer, but from local columns of hot air rising over the hotter spots in the iron and passing into the field of the bolometer-aperture at a volumetric rate, as appears from the present argument, which is the same in the rarefied as in the denser air. It has been shown that the disposition, or thermal condition, of the components of the radiating mass at the same mean temperature, and thence the combined radiation of the whole, is different according as the cylinder is heating or cooling, and that the true air radiation probably lies near the values obtained with negative thermal rates. It is also found that the emission of gaseous radiation increases at a more rapid rate than the temperature, so that if ordinates represent radiation and abscissæ temperatures, the curve should be concave upward. Nevertheless, with rapid heating the observations are well represented by a straight line, evidently because the diminishing rate of heating at the higher temperatures gives less powerful convection. Small but excessively heated volumes, giving the larger part of the radiation, then become less predominant, as equilibrium approaches, and the diminution of the convection-correction cuts off the more rapid rise of the energy-curve which would otherwise occur at higher temperature.

It is possible that the apparent radiation of carbon dioxide, at constant temperature, increases at low pressures (as indicated in Table 47, p. 67) by not more than 30 per cent. of the value at normal pressures; but the variation is not beyond the limits of error of the observations on which it rests.

According to Dulong and Petit (*loc. cit.*), the cooling power of air, as far as it depends on pressure, is represented by the ratio $p^{0.45} \div p_1{}^{0.45}$, and that of carbon dioxide by the ratio $p^{0.517} \div p_1{}^{0.517}$. Hence the influence of change of pressure upon convection is greater for carbon dioxide than for air, but this is open to various interpretations. A part of the removal of heat by gaseous contact is due to mass convection, and part to the penetrative power of the flying molecules, as G. Johnstone Stoney has demonstrated (On the Penetration of Heat across Layers of Gas, *Phil. Mag.* (5), vol. 4, p. 424, Dec., 1877); but in either mode the effect finally depends partly on the capacity of the gas for heat, and this, for equal volumes, is greater for carbon dioxide than for air in the ratio $\frac{3307}{2375} = 1.393$; while in part the magnitude of the effect is connected with molecular velocity, which is greater for air in the ratio $\frac{487}{397} = 1.227$. The combined effect can only be found by experiment. At normal pressure the cooling by carbon dioxide is 0.965 of that by contact with air, but at low pressures the relation is reversed.

METHOD D.—RELATIVE RADIATION OF AIR AND STEAM, AND OF CLEAR AND SMOKY AIR.

In this method the cylinder was provided with a pressure gage, recording in pounds per square inch to a pressure of 15 pounds above the normal. The cylinder then served as a reservoir for either compressed air or steam. On opening a stopcock the air, or steam, issued from a hot brass tube, one-half inch in diameter, as a hot jet between the bolometer and a blackened screen containing water at the temperature of the room. The bolometer was protected from air currents by a rock-salt plate. In the first experiments partially dried air was used. Three dishes containing flocculent phosphoric anhydride, were placed on the floor of the compression cylinder, and air, compressed by a pump, was forced into the heated cylinder, but was not allowed to stand long enough to become thoroughly dried.

The objections to the method are that the amount of the radiating gas can not be accurately

measured, and that its temperature, after leaving the nozzle, is lowered by mixture with cold surrounding air. For these reasons the deflections have only a relative value. The temperature of the room, owing to the escape of considerable volumes of hot air or steam, rose rather rapidly, but was kept within bounds by opening windows.

September 28, 1895.

Temperature of room varying from 16°.7 C. to 22°.0.

Mean dew point, 8°.3 C. Pressure of water vapor, 8.15 mm., or 8.37 grams per cubic meter.

Temperature of air blast on issuing, (1) 146°, (2) 221°.

Mean deflections, (1) 1.94 div., (2) 3.45 div.

September 30, 1895.

Mean temperature of room, 15°.6 C.

Mean dew-point, 6°.1 C. Pressure of aqueous vapor, 7.02 mm., or 7.27 grams per cubic meter.

After several charges of steam had been allowed to escape in order to remove the air from the cylinder, readings were begun. The deflections increased as the steam became purer. The following successive readings were taken: + 4.6, + 5.8, + 7.9, + 8.1, + 9.8, + 9.8, + 10.3, + 11.0, +9.5, + 11.0, + 11.6, + 11.0. The temperature having fallen slightly during the last readings, the cylinder was left to heat a little longer, and the final measures were made.

Temperature of steam blast on issuing, 202° C.

Mean deflection, + 12.39 div.

Corresponding air deflection, + 3.07 div.

Steam radiation four times as great as that of air. The undried air between the bolometer and the jet has probably absorbed more of the aqueous radiation than of that from the air, so that the ratio is, if anything, too small.

The superheated steam, on issuing, formed mist, and a part of the radiation comes from finely divided liquid; but the next experiment does not indicate that these condensed particles can have any great effect on the result.

In order to test the possibility of appreciable radiation from fine particles suspended in air, two wide-mouthed bottles were prepared with dipping inlet and free outlet tubes, the first one-fourth filled with strong ammonia water, the second containing about as much hydrochloric acid. Air from a foot bellows was blown through the coupled flasks, and a dense column of chloride of ammonium smoke arose immediately in front of the hot blast nozzle. As soon as the hot-air blast was turned on, this cloudy column was sheared off and mingled with the hot air. About one-fourth as much air issued from the smoke jet as from the hot blast, but the latter can not have been cooled thereby much more than in the ordinary suction and mingling of the surrounding air. The particles being excessively fine, and comparable in their dimensions with the shorter waves of light, as shown by the blueness of the smoke where it was thinner, the microscopic crystals must have taken the temperature of the air in which they were immersed almost instantly. The cloud appeared fully as dense as the mist from the condensed steam in the previous experiment.

October 3, 1895.

Temperature of room, 17°.7 C. to 18°.8.

Mean dew-point, 4°.4 C. Pressure of aqueous vapor, 6.24 mm., or 6.50 grams per cubic meter.

Temperature of hot-air blast, 200° C.

The range of pressure was a little lower than in the experiments of September 28, and the deflections are therefore a little smaller, but all are comparable with each other.

TABLE 49.

First series.	Second series.	Third series.
Air clear.	Air cloudy with NH_4Cl.	Air clear.
div.	*div.*	*div.*
+1.6	+2.0	+2.4
2.7	1.8	2.0
1.7	2.6	1.2
2.3	1.3	0.7
2.4	1.3	4.0
0.7	2.8	2.1
3.9	2.0	2.8
2.0	1.1	1.2
1.5	2.5	1.4
1.5	1.5	1.2
1.2	2.1	2.3
Means +1.95	+1.91	+1.75

There is no appreciable difference between the radiation of clear and of smoky air in small masses, but it would not be safe to generalize, from this experiment, in regard to radiation from large masses of smoky air.

COMPARISON OF SOME OF THE PRECEDING RESULTS WITH THOSE OF TYNDALL.

The experiment suggested by Professor Abbe in its simplest form (Prefatory note, pp. 1–2) has been partly realized in Method D, with the exception of the unessential addition of a background at the temperature of melting ice, and it has also been performed by Tyndall (*Contributions to Molecular Physics in the Domain of Radiant Heat*, p. 42 *et seq.*, American edition of 1873.) As a method of heating an air jet, Professor Tyndall's placing of a hot copper ball within a ring nozzle may have been efficient, but neither the temperature nor the mass of the air can be accurately measured in this way. The results are therefore only qualitative. The deflection from hot air being 0°, that from carbon dioxide is given as 18° (p. 43 *loc. cit.*); but this does not fully express the facts. It is true that when air was turned on through the nozzle the deflection did not increase, but hot air was already passing before the thermopile by simple convection. We read further:

> The radiation from air, it will be remembered, was neutralized by the large Leslie's cube, and hence 0° attached to it merely denotes that the propulsion of air from the gas holder through the Argand burner (or annular nozzle) did not augment the effect.

The 18° from carbon dioxide is therefore a differential effect, and requires the original deflection, without compensating cube, for its interpretation, but this is nowhere stated.

The jet of heated gas in Tyndall's experiment was of relatively small thickness. With a deeper layer the relative position of the two gases in question, as radiants, may be more nearly equal, since, as I have shown, air radiation from layers increasing up to several feet in thickness, varies nearly as the depth, while the radiation of carbon dioxide soon reaches a maximum.

Variations in the ratio of radiation with increasing depth are noteworthy in other gases, as in Tyndall's *Contributions* (p. 97), where a layer of olefiant gas (C_2H_4) having a depth of eleven units, radiated 1.62; and one of air of the same depth, containing one-sixtieth of ether-vapor $(C_2H_5)_2O$, radiated 5.82, the radiation from unit-depth of each gas being taken as unity.

The figures quoted above for radiation of air and carbon dioxide are of an indeterminate ratio, but the absorption of 33 inches of carbon dioxide for radiation from a copper plate, "raised to a temperature of about 270° C." (*loc. cit.*, p. 72), is stated (*loc. cit.*, p. 80) to be ninety times that of air. Even if the radiations of large masses of air and carbon dioxide are equal at some specified temperature, those of thin layers or jets must nevertheless be very unlike, the radiation from the thin jet of air being much smaller than that from a carbon dioxide jet. Other temperatures may yield different radiation-ratios for the two gases, while absorption varies at a still different rate. Consequently, no safe inference as to radiation-ratios can be drawn from those for absorption.

This is shown by the following observations by Paschen for the principal band in the spectrum of carbon dioxide at 4.25μ (*Wied. Ann.*, Bd. 51, S. 26, 1894):

TABLE 50.

Temperature of 7 cm. layer of CO_2.	Intensity of radiant emission.	Absorption by hot + cold CO_2.
° *C.*	*mm. div.*	*Per cent.*
17	0	89
183	17.5	77.5
290	60	68.6
377	118.7	36.7
480	261	19

The absorption is that produced within the limits of the band on the spectral energy-curve of blackened platinum at 400° to 500° C. The small remaining absorption band at the highest temperature has a wave-length 0.17μ shorter than the corresponding emission band, and is due to cold carbon dioxide in the air of the room, the radiation of the hot gas very nearly neutralizing the absorption by the hot gas at 480°.

On page 95 of the *Contributions*, Tyndall gives the ratio of apparent radiations from carbon dioxide and air, dynamically heated by compression, as 3:1, and on page 186 deflections are given whose ratio is 2:1. But these figures are not considered entirely trustworthy, since the radiation measured is supposed to be, to an uncertain extent, that of the end plate and walls of the containing tube, heated by contact with the hot compressed gases; and any differences in the observed radiation are to be attributed partly to the varying readiness with which heat is transferred by conduction and convection from the gas to the solid, and partly to differences in the amounts of heat produced by compression and transferred in this manner. Professor Tyndall, in pointing out some of the defects of the arrangement, says:

A brass tube 3 feet long and very slightly tarnished within was used for dynamic radiation. Dry air on entering the tube produced a deflection of 12°. The tube was then polished within and the experiment repeated; the action of dry air was instantly reduced to 7°.5. The rock-salt plate at the end of the tubs was then removed and a lining of black paper 2 feet long was introduced. The tube was again closed, and the experiment of allowing dry air to enter it repeated. The deflections observed in three successive experiments were 80°, 81°, 80° [corresponding to a force nearly 70 times as great as the first]. * * * A coating of lampblack within the tube produced the same effect as the [black] paper lining; common writing paper was almost equally effective. (*Loc. cit.*, p. 187.)

Now, the paper, being a poor conductor, must acquire on its inner and radiative surface, by direct contact with the dynamically heated gas, a higher temperature than the brass, in which any gain of surface temperature is quickly distributed to deeper layers of metal; but the thin coating of lampblack, backed by conducting metal, is in an intermediate position as a conductor, and might be expected to take on its radiating surface a temperature at any rate lower than that of the paper; yet both blackened paper and blackened brass are said to have behaved alike. Tyndall's explanation that the deflection of 7°.5 is mainly due to radiation from brass to which heat from the compressed air has been transferred, can hardly be maintained without modification, since blackened brass is not 70 times as good a radiator as bright brass, and no inconsiderable part of the 7°.5 may have been true air radiation. I shall return to this point subsequently (p. 110) with fresh material for a more searching test of its truth.

The long tube in Tyndall's research was made of polished metal, and the thermopile was provided with its conical polished reflector, in order to secure the advantage of larger galvanometer deflections, through multiple reflections at large angles of incidence on the inner walls of the tube in those experiments where an independent source of radiation was situated at or beyond the farther end of the tube. When such a tube is used for the dynamic heating of a gas, a large part of the heat produced by gaseous compression is unquestionably transferred to the walls of the tube; but since the mass of the gas and its thermal equivalent are small, while those of the tube are at least several hundred times greater, the tube can not become much heated unless the process is repeated a great many times. The large deflections from lampblack and paper are possibly

produced by a special condensation and development of heat in the pores of these substances. The argument on page 186 of the *Contributions*, which makes a "residual deflection of 6°" (after absorption by an extra 13 inches of quiescent carbon dioxide) represent the radiation of polished brass, does not appear to be conclusive, and, in fact, is put forth rather as a surmise.

Admitting the deflections to be of genuine gaseous origin, Tyndall's observations would make a 3-foot layer of carbon dioxide radiate two or three times as much as air. In my experiments the air apparently radiated twice as strongly as the carbon dioxide. In view of the very powerful radiation from water-vapor, and of the difficulty with which this substance is completely eliminated, it may be urged that my samples of air were not dry; but since greater precautions were taken in drying the air than in drying the carbon dioxide, the latter being merely passed through several flasks of porous calcium chloride, while the air, in some of my experiments, had stood for a week in contact with phosphoric anhydride, I do not think that the larger radiation, where air was used, can have proceeded from aqueous vapor in my samples. Only one of my air series gave deflections as small as for carbon dioxide, and this I have had to discredit, owing to a deterioration of the rock-salt plate.

Thus far we meet only uncertainty and discrepancy, but if the reader will have patience all of this shall eventually be cleared away.

It is desirable to have a more careful analysis of Tyndall's experiment than is given in the original memoir. Where the most distant part of the tube was set off as a radiant chamber by a rock-salt partition the direct radiation of its contained gas or walls was received under a smaller angular aperture and with proportionally smaller effect than where the partition was nearer to the thermopile; but the concentration of the beam reflected from the polished cylindrical walls of the tube was nearly the same in either case. The diameter of the tube is not stated. I will assume it to have been 2.4 inches, as in another case, and the distance of the thermopile from the nearer end of the tube to have been 6 inches, and thus compute the angular areas of the sections on these assumptions. The lengths and deflections in the following table are taken from Tyndall's Table XXXV for carbon dioxide, and the radiant energies are deduced from the deflections by the calibration of the galvanometer. (*Contributions*, p. 57.)

d_1 is the distance in inches to the nearest section.
$d_2 =$ " " " " " " farthest "
$l = d_2 - d_1 =$ the length of the radiating column.
$a_1 =$ the angular area of the nearest section.
$a_2 =$ " " " " " farthest "

TABLE 51.

	1	2	3	4	5	6
d_1	52.6	40.0	19.1	6.0	6.0	6.0
d_2	55.4	55.4	55.4	19.1	40.0	52.6
l	2.8	15.4	36.3	13.1	34.0	46.6
a_1	7	12	32	511	511	511
a_2	6	6	6	52	12	7
$(a_1+a_2)\div2$	6.5	9	29	281.5	261.5	259
Deflection	1	3.7	16.8	17.5	23.3	33.6
Radiation	1	3.7	17.2	18.0	25.7	48.6

Between (4) and (5) there is an increase of 20.9 inches in the length of the radiating column, and the radiation is greater by 7.7 units; but with a further addition of 12.6 inches to the length in (6), the radiation gains 22.9 units, or three times as much as for the larger increment of length in (5). Table XXXIV, for carbon monoxide, gives a very different relation for the same distances, the increment of radiation in (5) being 10.4 units, and in (6) 6.0 units, numbers which are nearly proportional to the gain in length. I have no hesitation in saying that the deflection from CO_2 in (6) is a mistake. The 33°.6 is possibly a misprint for 23°.6, since, as I have shown, there is no increase in the radiation of carbon dioxide beyond the third foot.

The deflection in (1)—Table 51—is too small for use; but with a trifling addition to the radia-

tions in (4) and (5), reducing them to the lengths of (2) and (3), we may make the following comparison:

TABLE 52.

Length of radiating column.	Radiation CO_2.	Ratio.	Mean angular area.	Ratio.
Inches.				
36	17–26	1:1.53	29–261	1:9
15	4–19	1:4.75	9–282	1:31
Ratio of ratios,		1:3.10		1:3.44

The changes seem to be mainly due to differences in the angular area, but this influences principally the radiation which comes directly to the thermopile, and the total radiation from the gas is made up approximately as follows:

Length.		Reflected radiation.	Direct radiation.	Total.
15 inches	(2)	3.5	+ 0.5	= 4.0
	(4)	3.5	+ (0.5 × 31)	= 19.0
36 inches	(3)	15.9	+ 1.1	= 17.0
	(5)	15.9	+ (1.1 × 9)	= 25.8

These radiations appear to be genuine, but there is no conclusive evidence that the radiation of polished brass has contributed to them appreciably. The observations on air are not given in detail, and we only know from page 186 that whereas the 3-foot layer of CO_2 gave a deflection of 16°.8, dry air gave 8° or 9°.

The temperatures of the gases are not so easily found. In general, the temperature of a gas being the sum of the kinetic energies of its molecules, divided by their number, may be very differently constituted according as the limits of variation of molecular velocity are wide or narrow. Radiation and absorption within the gas need also to be considered. In the present case the radiation has been measured in the midst of a complex series of operations, and we do not know even approximately what proportion of the heat of compression has been ceded to the metal. Professor Tyndall has attempted a thermometric measurement of the temperature of the dynamically heated gas, which may be given for whatever it is worth. He "had the tube perforated and delicate thermometers screwed into it air-tight. On filling the tube the thermometric columns rose, on exhausting it they sank, the range between the maximum and minimum amounting in the case of air to 5° F." (*loc. cit.*, p. 45). If the proportion of heat transferred to the walls is the same in the two gases, we must conclude that at excesses of a few degrees carbon dioxide radiates more than air; but the observation is open to the interpretation that the proportion of heat given to the walls is not the same for either gas, and the precise ratio has still to be determined. Some variations in the ratio of gaseous radiations at different temperatures need not surprise us, since the radiations are made up of bands of very different wave-lengths with various rates of increase by change of temperature. Even solid bodies may have spectral energy-curves of quite different shape, as I have shown in a comparison of the spectra of the Welsbach light and of the illuminating gas flame of an Argand burner. ("Further considerations in regard to laws of radiation," *Astrophysical Journal*, vol. 4, p. 45, June 1896). The relative radiations of particular wave-lengths for these lights vary nearly as 1 to 4 in different parts of the spectrum, the spectral energy-curves crossing and recrossing, and much wider ranges occur in gases where each band has a law of its own. Before arriving at a more definite conclusion a further study of the relation between gaseous radiation and absorption must be made.

MODIFICATION OF ATMOSPHERIC RADIATION BY THE ABSORPTION OF CONSTITUENT GASES AND VAPORS.

Having made a preliminary clearing of some of the sources of error incidental to the apparatus, the method of observation, and the properties of matter, we are now prepared to take up a very important subject—the modification of radiation from gases or solids by gaseous absorption.

Gaseous radiation and absorption are so intricately interwoven that one can not be explained without also considering the other. Observations of gaseous absorption exist in great abundance, but those on gaseous radiation are comparatively few. It is largely in consequence of this one-sided distribution of evidence that so many questions in this department remain open, and that others which have really been settled for a long time do not obtain recognition or are reopened on insufficient grounds.

The chief absorbent of the Earth's atmosphere is water-vapor, but its action is complicated by the relation between vapor and mist. Even considerable changes in atmospheric aqueous vapor in warm weather, if unattended by misty condensation, produce only slight variation in the direct rays of the midday sun, not, however, because water-vapor does not exercise a great absorption, even on solar rays, but because so much moisture is always present in warm weather that nearly all of the rays absorbable by aqueous vapor have been eliminated, and the remaining radiation is comparatively transmissible. Haze, however, of whatever description, whether formed of mineral particles, smoke, or finely divided liquid or solid water, acts at all seasons, and independently of the amount of the vapor of water dissolved in the air. Mist and haze have little effect on the emission of radiations of long wave length from air by virtue of its own temperature, or on the transmission of long ether-waves by the atmosphere, but they have great influence in stopping and scattering those short ether-waves which are especially prominent in sunlight.

Ferrel says (*Recent Advances in Meteorology*, p. 56, ¶ 43, 1886) "the difference in the intensity of the solar rays at the earth's surface at sea level, when the atmosphere is very clear and when it is somewhat hazy, is small, and therefore the whole diminution of intensity in passing through is due mostly to the pure atmosphere;" but this is not correct. The *direct* rays of the sun are much impeded by haze, but are nevertheless nearly as effectual in warming the earth's surface indirectly, because a large part of the rays scattered by the haze still reaches the earth as sky radiation, which bears an increasingly large proportion to the direct solar rays as haze grows denser. In a general way, this influence of the scattering of light by fine particles is recognized by Ferrel on page 59 of the same work, but its application to the point noted on page 56 escaped his attention.

Other inconsistencies occur in the same connection. Thus, on page 59, we read: "It is thought that *pure dry air absorbs very little* of the sun's [radiant] heat in its passage through to the earth. If so, *the loss of intensity must be caused mostly*, in this case at least, *by the irregular reflections* in all directions." But at the end of the same paragraph it is said that *these reflections* "*depend very much in some way upon the vapor* contained in [the clear atmosphere] where it exists. But as this is found mostly in the lower strata near the earth's surface, and only in a small measure in the middle and upper strata of the atmosphere, *its effect is small in comparison with that of the whole depth of a dry atmosphere.*" The only idea which I can derive from the passages which I have italicized is that pure, dry air influences the sun's radiation very little, and mainly by irregular reflection, while water-vapor is even less effective. The last inference is further emphasized in paragraph 44, page 56: "According to the experiments of Dr. Tyndall on the diathermancy of a small portion of air contained in a tube, with regard to heat radiations from terrestrial sources the diathermancy of clear air depends almost entirely upon the aqueous, invisible vapor in it, seventy times as much heat, according to the result of the experiments, being absorbed by it as by the dry air through which the rays pass. This result, however, differs very much from that which had been obtained by Magnus in experiments on the same subject, and this gave rise to considerable discussion between these physicists, Magnus maintaining that the absorption of heat in Tyndall's experiments was by a film of condensed vapor on the inside of the tube through which the rays passed. And this seems really to have been the case, according to experiments which have since been made to verify the results." Nevertheless the opinion is repeatedly expressed elsewhere (as on page 57 *loc. cit.*) "that aqueous vapor in some way diminishes the diathermancy of the atmosphere to terrestrial heat radiation." The only inference which I can draw is that the entire subject was in a state of hopeless confusion in the mind of one who has elsewhere exhibited extraordinary keenness of intellectual perception. The authority of so great a master as Ferrel perhaps has something to do with the fact that the subject still remains obscure. Most of the errors have been repeatedly refuted, but the refutations fail to attract attention.

The fallacy of Magnus, who asserted that he got an absorption of 14.75 per cent. from dry air,* where Tyndall found practically none, has been abundantly exposed. Tyndall showed that the glass plates which Magnus used to close his glass vacuum tube must have been heated by absorption of the radiation which passed through them, acting thus as secondary sources of radiation, and that, being chilled by convection, their thermal effect was diminished on admission of dry air. Tyndall used end plates of the feeble absorbent, rock-salt, whose thermal change was relatively small, and this prevented the error in question in his measures. With the glass plates used by Magnus the absorption of so potent a substance as aqueous vapor, being greatly masked or reduced by the nontransmission of radiation by glass in that region where aqueous absorption is chiefly exercised, was further completely overwhelmed by convection, and remained undetected from these causes, combined with lack of sensitiveness in the measuring apparatus.

On the other hand, Tyndall does not completely meet the criticism that a portion of the absorption attributed by him to aqueous vapor may have been due to a very thin film of liquid water condensed on the metallic reflecting surface of his tube, but contents himself with showing that substantially the same relative absorptions were obtained when blackened tubes were used, and finally with tubes so wide that the radiant beam concentrated by a rock-salt lens did not touch the walls, so that condensation could not have had any material influence on the result. (*Contributions*, etc., p. 394.) Magnus, in instituting his criticism, overdid the matter, claiming that all of the absorption, measured by Tyndall and attributed by him to aqueous vapor, was due to the liquid film. Lecher and Pernter (*Sitzb. der k. Akad. der Wissensch. zu Wien*, July, 1880; *Phil. Mag.*, (5) Vol. 11, p. 1, Jan., 1881) in repeating the charge have overlooked the experiment with the rock-salt lens. The claims so far made rest upon mere assertion, but the following considerations, based on internal evidence drawn from the experiments as published, indicate that further elucidation is desirable.

It is to be remembered that in his earlier measures, owing to the insensitiveness of his heat-measuring apparatus, Tyndall used a wide-angled conical reflector to concentrate the rays upon his thermopile, and transmitted the radiant beam through polished tubes in order that radiation, proceeding from the source under a wide angle, might be fully utilized by multiple reflections. Of course the mean path of the rays was somewhat longer than the tube.

Professor Tyndall makes the following statement:

The absorption is exerted when only a small fraction of an atmosphere is introduced into the tube, and it is proportional to the quantity of air present. This is shown by the following table, which gives the absorption, by humid air, at tensions varying from 5 to 30 inches of mercury:

HUMID AIR.

Tension.	Absorption.	
	Observed.	Calculated.
Inches.		
5	16	16
10	32	32
15	49	48
20	64	64
25	82	80
30	98	96

* The numerical value depends entirely upon the disposition of the apparatus, and has no connection with the absorption of air. Thus, Dr. Franz, by using a 3-foot tube lined with black paper, which cut off internal reflection and diminished the heating of the glass end plates, had obtained an apparent absorption of 3.54 per cent. for dry air, and Magnus, with a nearly similar tube 1 meter long, got 2.46 per cent., concerning which Tyndall says: "Professor Magnus himself finds that the quantity of [radiant] heat transmitted through his unblackened tube is 26 times that which passes through his blackened one where the oblique radiation is cut off. In the case therefore of the naked tube, the flux of [radiant] heat sent down by the heated glass plate adjacent to the lamp, to its fellow at the other end, and likewise the [radiant] heat sent directly from the lamp to the same plate are greatly superior to what they are in the case of the blackened tube. The plate adjacent to the pile becomes therefore more highly heated, and as its chilling is approximately proportionate to the difference of temperature between it and the cold air, the withdrawal of heat will be greatest when the tube is unblackened within. * * * It is, I submit, not a case of absorption, but of direct chilling by the cold air." (*Contributions to Molec. Phys.*, pp. 419–420.)

The third column of this table is calculated on the assumption that the absorption is proportional to the quantity of vapor in the tube, and the agreement of the calculated and observed results show this to be the case, within the limits of the experiment. It can not be supposed that effects so regular as these, and agreeing so completely with those obtained with small quantities of other vapors, and even with small quantities of the permanent gases, can be due to the condensation of the vapor on the interior surface. When, moreover, 5 inches of air were in the tube, less than one-sixth of the vapor necessary to saturate the space was present. The dryest day would make no approach to this dryness. Condensation under these circumstances is impossible, and more especially a condensation which should destroy, by its action upon the inner reflector quantities of [radiant] heat so accurately proportional to the quantities of matter present. (*Heat Considered as a Mode of Motion*, Am. Ed., pp. 405–406, 1869.)

In this quotation the air is said to have been humid, and yet, when reduced to a pressure of one-sixth of an atmosphere, to have contained "less than one-sixth of the vapor necessary to saturate the space." But if the air was anywhere near saturation at the ordinary pressure, it must have been supersaturated when reduced to a pressure of 5 inches, a fact which was perfectly well known to Tyndall, since he has described it on page 46 of the same work. I can only reconcile these statements by supposing that either Tyndall inadvertently overlooked the increase of relative humidity in air at reduced pressure, when writing this passage, or else that the description of the air as "humid" is very misleading; and I submit that the case is not quite so axiomatic as its author maintained, and that precipitation of liquid water on the inner walls of the tube at low pressures, if we take the first horn of the dilemma, may have diminished the reflecting power of the polished walls, while the lessening of the vapor contents at the same time would render the air more transmissive, giving a certain degree of compensation which is not incompatible with an increment of vaporous absorption by no means proportional to the air pressure.

On page 404 (*Heat as a Mode of Motion*) we read:

The air of the laboratory was dried and purified until its absorption fell below unity; this purified air was then led through a U-tube filled with fragments of perfectly clean glass moistened with distilled water. Its neutrality, when dry, showed that all prejudicial substances had been removed from it and in passing through the U-tube it could take up nothing but the pure vapor of water. The vapor thus carried into the experimental tube produced an action ninety times greater than that of the air which carried it.

Tyndall has pointed out (*Contributions*, p. 387) that merely letting dry air bubble through cold water is not a perfect means of moistening it, but passage through U-tubes filled with wet glass is an effectual method of producing saturated air. The moistening described on page 404, *Heat as a Mode of Motion*, is not explicitly stated to apply to the conditions of the experiments with "humid" air on page 405; but in the *Contributions* (p. 411) it is stated the amount of aqueous vapor capable of being taken up by air at a temperature of 15° C., produced an absorbtion forty times that of air; and again (p. 412), we read: "It is with this common outer air, and not with air artificially saturated with moisture that I find the absorption of aqueous vapor to be fifty or sixty times that of the air in which it is diffused." Numerical values depend upon absolute quantities of vapor and these upon temperatures and concomitant details which are provokingly infrequent in Tyndall's memoirs, but from these supplementary statements one would infer that the humid air which gave an absorption of 98 in the table already quoted, must have been very nearly saturated, and that the measures at low pressures are open to criticism. Since, however, the experiments of Aitken show that air which is free from dust may be supersaturated without precipitation, I do not mean to assert that the precipitation did necessarily occur.

Abandoning tubes, Tyndall tried the method of displacing the free air between a cube of boiling water and the thermopile, alternately by air dried by fresh chloride of calcium and by air moistened by passing through a cylinder filled with fragments of quartz moistened with distilled water (*Heat as a Mode of Motion*, p. 407), obtaining a differential deflection of about 15°, corresponding (by p. 403, *loc. cit.*) to an aqueous absorption of about 2 per cent. (Temperature not mentioned.)

Hoorweg (*Pogg. Ann.*, Bd. 155, S. 385–402, 1875) repeated this experiment. No difference as great as 0.2 per cent. could be found at first between the absorption of dry and moist air, as exercised upon radiation from a Leslie's tube. The transverse dimensions of the air blast are not explicitely stated, but probably the air issued from a narrow jet. He then repeated the experiment with a moistener 50 cm. long and 9 cm. broad, obtaining for the absorption of moist air 1.7 per cent. (temperature 9° C.); and finally with a moistener 100 cm. long and 9 cm. broad, the source being a black copper plate heated by a Bunsen burner, he obtained, with an air

temperature of 7°.5 C., an absorption of 2 per cent. by moist air, which might perhaps be doubled by substituting a source at 100° C.

I fail to see the cogency of some of the remarks in this paper. The final conclusion in regard to aqueous absorption is stated by this author as follows:

From this I believe that 100 meters of ordinary air are still not by a long way in condition to produce the results which Tyndall already obtained from 10 feet, namely that 10 per cent. of the entering rays would be absorbed.

In regard to this statement, I can only say that its truth or falsity depends upon what is to be understood by "ordinary air." The temperature and humidity of what would commonly be considered as ordinary air vary so widely with the locality and the season, that without numerical definition of water contents such an assertion is too loose to be of any value. Tyndall's statement,* criticized in this passage, is drawn up in the same undefined way and is equally devoid of meaning, unless interpreted by other passages.

Dr. H. Buff (*Pogg. Ann.*, Bd. 158, S. 177–213, 1876) used an apparatus patterned after that of Magnus (*Pogg. Ann.*, Bd. 112, S. 531; *Phil. Mag.* (4), vol. 22, p. 85, 1861), but with a few alterations which Dr. Buff considered improvements. In fact, results were obtained which differed from those of Magnus, and indicated the source of some of his errors which had already been explained by Tyndall. Dr. Buff, however, appeared to think that he had overcome these errors, whereas it is evident that the method as conducted by both Magnus and Buff is unsound.

Instead of the glass-walled vessel to hold hot water which was used by Magnus, Buff had a vessel of sheet brass, polished on the bottom, and radiating downward upon a thermopile. Double side walls, stuffed with cotton wool, prevented rapid cooling. The metal vessel rested air-tight on a glass cylinder 20 cm. high and 7.5 cm. wide, which, in turn, was made air-tight on the plate of an air-pump. The thermopile of iron and german-silver wire, beaten out to a breadth of 12.5 mm. and soldered, was 23 mm. below the heating surface. In the first experiments the air was dried by passing it slowly through a 40-cm. tube of fused chloride of calcium. It is evident that the heating effect observed was a complex of convection, conduction, and radiation from a variety of sources. The maximum deflection, which was attained after a lapse of fourteen to twenty-two minutes, was due mainly to slow heating of the glass cylinder by conduction, and to the convection and radiation started by the resulting disposition of heated walls. The effect continued for thirty minutes, although the temperature of the hot water meanwhile had fallen continuously.

Dr. Buff having obtained, as he imagined, a transmission of 47.7 per cent. from 4.5 cm. of dry air, next increased his layer of air to 10 cm. The results were not such as to meet his expectations. "The absorptive power of air, instead of proportionately increasing, as I had supposed," he says, "seemed to decrease from the 50 per cent. previously observed to 20 and even 15 per cent." Yet notwithstanding this most improbable result, his confidence in the accuracy of his method and its interpretation (which differed in no important respect from that of Magnus) remained unshaken, while Tyndall's was branded as "unreliable," and these measures of Magnus and Buff have been repeatedly quoted as authoritative, in spite of their complete overthrow by Tyndall.

Blackening the bottom of Buff's brass vessel containing the hot water increased the deflections "but feebly, though the radiating power of the source of heat must have been 6 or 7 times greater than previously;" a result which proves that only a minute part of the observed effect can have been due to the radiation of the blackened brass, and which consequently demonstrates that the large variations observed were at any rate not due to absorption of radiation by the inclosed gases.

Only one other point in this paper requires mention, namely, the assertion that a plate of rock-salt, 0.3 cm. thick, absorbs 40 per cent. of the radiation from a vessel of hot water, and that

* "Regarding the earth as a source of heat no doubt at least 10 per cent. of its [radiant] heat is intercepted within 10 feet of the surface." (*Heat as a Mode of Motion*, p. 404.) It is to be borne in mind that this refers especially to radiation from a surface which is commonly moist and that such radiation through nearly saturated surface layers of air may be especially obstructed by aqueous vapor. (See *Contributions*, p. 395, and this bulletin, p. 90 to 105.)

the thermochrose of rock-salt and dry air are similar,* Buff maintaining that Tyndall found no absorption by air because his rock-salt plates had already sifted out the rays for which air is opaque. Professor Tyndall, in his reply (*Proc. Royal Soc. London*, vol. 30, p. 10, Dec., 1879), points out that he had already (see *Heat as a Mode of Motion*, p. 399) tried the experiment of bringing the naked face of his thermopile "within one-twentieth of an inch of [the] terminal plate of rock-salt. There was not the slightest alteration of the previously obtained result. Dry air, as before, behaved like a vacuum." The course of the radiation was here through a succession of vacuum, salt, vacuum (or dry air at pleasure), salt, and one-twentieth inch of normal air to the pile. There was little probability that so thin a layer of air as one-twentieth inch could sift out and totally remove any appreciable amount of a special class of rays; and Melloni's measurement, which made the transmission of a plate of rock-salt, 0.26 cm. thick, as great as 92.3 per cent. of the total radiation, almost all of the loss being due, not to absorption, but to nonselective surface reflection, might well have been deemed sufficient to prove the fallacy of Buff's suggestion that a few cm. of air or a small fraction of a cm. of rock-salt can totally remove a large percentage of the radiation; but to put the matter beyond all possible doubt, Tyndall constructed a new apparatus (*loc. cit.*, fig 1, p. 16) placing the thermopile in a chamber filled with hydrogen, protecting against hydrogen convection currents and radiation from side walls by diaphragms, and introducing a central variable chamber containing dry air, in which the thickness of the air layer could be varied from zero, when the inclosing rock-salt plates were in contact, to 3 inches, "which exceeds by more than 50 per cent. the thickness of the layer to which Professor Buff ascribes an absorption of 50 or 60 per cent." "Repeated experiments with this apparatus proved the absorption of the layer of dry air in the chamber to be *nil*."

The supposition of an identical absorption by rock-salt and air was then tested by comparing the transmission of a thick plate of rock-salt in vacuum with its transmission in air. There was no sensible difference. There is consequently no similarity in the thermochrose of air and rock-salt.

Finally, Tyndall shows that Buff's method, although defective "even when every care is bestowed upon it," may be improved. "A glass cylinder, 12 inches long and 2⅝ inches in diameter, is mounted on the plate of an air-pump. On it is placed a tin vessel with a brass bottom, intended to contain the water which warms the bottom or source of heat. A thermopile is mounted on the air-pump plate on which the cylinder stands, one of its faces being presented to the bottom of the tin vessel. The conical reflector is abandoned, a piece of tubing, blackened within, and intended to cut off the radiation from the sides of the vessel, being pushed over the pile. Instead of bringing brass and glass into direct contact, as in the apparatus of Professor Buff, a washer of non-conducting india rubber, an inch and an eighth in thickness, separates the one from the other. There is no chilling by cold water, and the distance of the pile from the source renders it difficult for heat to pass by convection from the one to the other." With this apparatus, instead of finding olefiant gas more diathermant than air, as Buff had done, Tyndall obtained an absorption of 33 per cent. from a depth of 11 inches of olefiant gas, while air and hydrogen did not differ appreciably from a vacuum in their readiness of transmission. The results agree with Tyndall's earlier measures obtained by other methods.

It might be supposed that such a complete exposure of the fallacy of Magnus' method, both in its original form and as modified by Professor Buff, would forever settle the questions at issue; and that Buff's further statement that he, like Magnus, found no difference between the absorption of dry and moist air would be taken for what it is worth, namely, nothing at all; but such statements as those quoted from Ferrel, made six years after this crushing rejoinder, show that old errors die hard.

Prof. W. M. Davis, in his *Elementary Meteorology* (p. 145, Boston, 1894), says:

> The action of water vapor on insolation and terrestrial radiation has been much discussed. Some have regarded it as diathermanous to insolation, but relatively opaque to terrestrial radiation, and have therefore attributed to it a controlling influence in determining the temperature of the atmosphere. More careful experiments have, however, shown that water in the truly vaporous state is as diathermanous as pure dry air to terrestrial radiation; and that it is only water in the liquid state that exerts a strong control over radiation from the earth. This appears to be confirmed by observations on the diurnal range of temperature under varying conditions of humidity. If the

* It will be shown subsequently (p. 114) that there is an analogy between the radiant powers of rock-salt and dry air, but not identity.

temperature of the air is well above saturation, the range is relatively strong; if near saturation, the range is diminished, even though no visible clouding of the sky occurs; if a thin hazy cloud is formed, the range is greatly reduced.

The experiments which have been interpreted in favor of the diathermancy of water-vapor have been refuted long ago, and Professor Davis, since the publication of his book, has given evidence that he no longer adheres to the erroneous doctrine there enunciated. (See his "Absorption of Terrestrial Radiation by the Atmosphere," *Science*, N. S. Vol. 2, p. 485, Oct. 11, 1895.) The diminution of the daily range of temperature with a clear sky, as saturation approaches, is to be attributed partly to a change in the quality of aqueous absorption, but also to the increase of water-vapor and its ascent to exceptional heights in the atmosphere in considerable quantity, whereby the escape of surface radiation is impeded by the strong aqueous absorption of the infra-red rays, especially for those between 5μ and 8μ, not far from the point where the maximum energy in the radiation from bodies at ordinary temperatures resides. The presence of large masses of water-vapor in the upper air may not always be indicated by high relative humidity at the surface, any more than by clouds, but it is evidenced by the strengthening of the rain-band, as seen in the spectroscope, as well as by the diminution of the diurnal range of temperature; and after heavy rainfall has depleted the upper air of moisture, the direct rays of the sun are intensified, and to a still greater degree the loss of heat by radiation from the earth's surface, so that the change of temperature between day and night reaches its greatest value, and at the same time the rain-band fades out, showing that it is the withdrawal of the invisible veil of water-vapor which has increased both radiation and daily range. The statement on page 32 of Professor Davis' book that "water vapor is, like clear air, a poor absorber of nearly all kinds of waves," and the doubt which is cast upon the theory that the atmosphere is a trap which allows solar rays to enter more freely than surface rays are permitted to escape, are both overthrown by the experimental demonstration of the efficacy of aqueous vapor as an absorbent of infra-red rays.

Prof. Thomas Preston in his *Theory of Heat* (p. 485, London, 1894) says in introducing the experiments of Lecher and Pernter (published in 1880): "But these new investigations, instead of settling the question in dispute between Tyndall and Magnus as to the comparative absorptions of dry and moist air, place the whole matter in a state of greater uncertainty. For whereas Tyndall found an exceedingly low absorption for dry and a high absorption for moist air, while Magnus found the same absorption for both, and that tolerably high, the results of the experiments of Lecher and Pernter show practically no absorption for either; or, in other words, both dry and moist air act as a vacuum toward radiant heat." These and numerous other less explicit statements in current scientific literature show that even down to the present day the question of the action of aqueous vapor upon telluric radiation is still regarded by many as an open one.

I proceed to the discussion of the last-named observations, which contain some puzzling but not inexplicable features. Lecher and Pernter (*Sitzb. der k. Akad. der Wiss. zu Wien*, July, 1880; *Phil. Mag.* (5), vol. 11, p. 1, Jan., 1881) by substituting a thin horizontal plate of lampblacked copper brought suddenly to 100° C. by a jet of steam, in place of the arched dome of glass heated by hot water in the original apparatus of Magnus, succeeded in shortening the time of exposure and diminishing the convection until they were able to confirm Tyndall's observation of the sensibly perfect transmission of radiation by dry air. But with a layer of 31 cm. of air they could detect no difference between the absorption of moist air and dry. Magnus' galvanometer and thermopile were too insensitive to measure this difference, even if his arrangement had been free from its other defects; but Lecher and Pernter's instruments apparently had the requisite delicacy, and we must seek elsewhere for the cause of their failure.

The face of the thermopile was covered with lampblack, which is very hygroscopic, and likewise the bottom of the radiating vessel. Whenever this was heated in moist air and in a closed vessel, moisture was driven off from the coating of the radiator and probably deposited to a sufficient extent upon the blackened thermopile to largely compensate by the development of latent heat for the slight diminution of radiation by only a few inches of moist air, while the radiation of the hot vapor (diminished by aqueous absorption) was added to that of hot metal. The short time of exposure (90 sec.) diminished the influence of convection currents, but favored the inclusion of a transitory phenomenon, like the evaporation of hygroscopically imbibed moisture.

The importance which has been attributed to the observation makes it desirable to analyze it

somewhat critically. Comparing measurements of the absorption of various gases and vapors by Lecher and Pernter with those made on the same substances by Tyndall, it will be seen that the differences between their results for the absorption exercised on the radiation from a blackened metal plate at 100° C. are too large to be neglected, and in the case of vapors the discrepancies are excessive. as the following table shows:

TABLE 53.

	Lecher and Pernter.				Tyndall.				
	Length.	Pressure.	Absorption.	*t*.	Length.	Pressure.	Absorption.	*t*.	(‡)
	cm.	*mm.*			*cm.*	*mm.*			
Chloroform, $CHCl_3$	31	70	0.0050	Temperature of source 100°.	126	13	* 0.216	Source 100°.	
Ether, $(C_2H_5)_2O$	31	13	0.0504		126	13	* 0.541		
Benzole, C_6H_6	31	42	0.0619		126	13	* 0.345		
Ethylene, C_2H_4	31	751	0.4826		5	762	† 0.328	Source 270°.	0.551
Carbon monoxide, CO	31	744	0.0660		5	762	† 0.068		0.076
Carbon dioxide, CO_2	31	748	0.0810		5	762	† 0.076		0.094

* *Heat as a Mode of Motion*, p. 441. (Conditions described p. 431.)
† *Contributions to Molecular Physics*, p. 170.
‡ Temperature of source 100° C. Masses of gas equivalent to those in the experiments of Lecher and Pernter.

To account for their discrepancies Professors Lecher and Pernter refer to observations of Regnault (*Mem. de l'Acad. Fr.*, t. 26). "Regnault has observed that the tension of vapors is less in vacuum than in a space filled with air, and he explains this as the result of condensation on the walls. This causes a diminution of the vapor tension, so that while in a vacuum compensation is instantly made by the liquid, in a space filled with air this requires time, and the full vapor tension is never reached."* Now, in the cases cited Tyndall employed an exhausted tube, into which his vapors were allowed to expand from a sample tube connected with a vapor flask, the vaporization being made "without the slightest ebullition" (*Contributions to Molec. Phys.*, p. 179), but since there were no special precautions to keep all parts of the vapor chambers at the same temperature, it is conceivable that, on the opening of the vapor flask into the sample tube, a portion of vapor condensed on the walls of the latter, and subsequently, when the lower valve was closed and the upper opened, this condensed liquid evaporated into the absorption tube. Thus there may have been a larger quantity of vapor present in the absorption tube than might have been expected from the temperature of evaporation. In this way we may explain the fact, commented on by Lecher and Pernter, that the pressure in the vapor flask, computed from Tyndall's data,

* This statement hardly expresses the facts of the original observations which are contained in *Mémoires de l'Académie des Sciences de l'Institut Impérial de France*, t. 26, p. 700, Paris, 1862. Regnault found that the density of aqueous vapor, relatively to that of air, increases as the saturation point is approached.

Relative humidity.	Relative density of aqueous vapor.	Relative humidity.	Relative density of aqueous vapor.
Per cent.		*Per cent.*	
100	0.64693	87.0	0.62499
96.4	0.63849	73.3	0.62140
96.4	0.62786	30.2	0.62078

Regnault himself says (p. 701): "The experiments which have been made at temperatures very near those of saturation give densities larger [than the theoretic density], and the difference is so much the greater as we approach nearer saturation. I conclude from this that the density of the vapor of water, *in the vacuum and under feeble pressures*, may be calculated after the law of Mariotte and according to the theoretic density, provided the fraction of saturation does not surpass 0.8, but that this density increases notably toward the state of saturation. This last circumstance may be due to two causes: either the vapor of water experiences, really, an abnormal condensation on approaching the state of saturation, or else a part of the water remains condensed upon the glass walls and only takes the gaseous state when the interior vapor is far from saturation."

Lecher and Pernter ignore Regnault's first explanation that aqueous vapor becomes abnormally condensed on approaching the point of saturation, but it will be shown subsequently that this condensation is a fact.

approaches the boiling point of the volatile liquid in several instances, whereas the experiments were actually conducted at a much lower temperature. But, admitting the truth of this part of the criticism and the uncertainty of the vapor densities computed from the relative volumes of sample and absorption tubes, the argument does not apply to experiments (such as those quoted in Table 53) in which the vapor pressures, *measured by a manometer*, fell far short of those for saturation at the presumed temperature. Tyndall is, unfortunately, very seldom explicit in describing his conditions of experiment, but it may be inferred from some of his statements that the temperature of his apparatus was in general that of the apartment, and not far from 15° C., at which temperature, and under complete absence of air, it is improbable that there can have been any appreciable liquid films condensed from the vapors in question. Moreover, the point can be subjected to a much more severe test.

Tyndall, in his *Contributions* (p. 171), gives a series of measurements in which not the vapor pressure, but the thickness of a layer of air saturated with ether-vapor, was varied. Here, if the absorption had been due to a film of liquid ether condensed on the rock-salt plates, the mere variation in the distance between these plates could have had no effect upon the transmitted radiation. In the next table Tyndall's results are given in comparison with a series by Lecher and Pernter, in which, however, it is the pressure of the ether-vapor which has been varied. Whether it is permissible to make comparison under these circumstances will be considered presently. The temperature in Lecher and Pernter's experiment was 7°.4 C., which fixes the pressure attainable at the upper limit at a figure probably lower than Tyndall's; but since Tyndall's greatest depth of air and saturated ether-vapor was only one-sixth of that used by Lecher and Pernter, the latter ought still to have had the greater absorption; nevertheless, according to their determination, the absorption was actually less. In Table 54, l is the length of the absorbent column, p is the pressure of the ether-vapor, t is the fraction of radiation from a lampblack surface transmitted by the ethyl ether, x is the exponential coefficient of transmission in the formula,

$$t = e^{-mx}$$

where e is the Naperian base, and m is the mass of absorbent vapor in a column of unit section. Without further data no absolute comparison is possible, but since m is proportional to lp, and l in the one case is constant and equal to 31 cm., p being constant in the other case, and probably about 35 cm., or nearly the same, p and l may be taken respectively in place of m in a preliminary computation of a multiple, nx, differing only slightly from x.

TABLE 54.—*Ether-vapor.*

Tyndall.					Lecher and Pernter.				
l	p	lp	t	nx for 1 cm. l	l	p	lp	t	nx for 1 cm. p
cm.	*cm.*				*cm.*	*cm.*			
0.127	35 ?	4.45	0.979	0.1672	31	1.28	39.68	0.9496	0.0404
0.254	35 ?	8.89	0.954	0.1854	31	4.12	127.72	0.8737	0.0328
0.508	35 ?	17.78	0.913	0.1792	31	7.86	243.66	0.7794	0.0317
1.016	35 ?	35.56	0.857	0.1519	31	12.52	388.12	0.6924	0.0294
2.032	35 ?	71.12	0.790	0.1160	31	23.33	723.23	0.5859	0.0229
3.810	35 ?	133.35	0.654	0.1115					
5.080	35 ?	177.80	0.649	0.0851					

For equal masses of ether-vapor the absorption and the exponential coefficient are considerably larger in Tyndall's series than in that of Lecher and Pernter; but in both the value of x increases as the absorbent mass diminishes,* and in nearly the same ratio, Tyndall's rate being slightly the greater. Thus, Tyndall's measures show that with a variation of the mass in the ratio, 1:20.00, there is a change in x in the ratio, 1:0.4590, while Lecher and Pernter, for a mass change in the ratio, 1:18.23, have a variation of x in the ratio 1:0.5673. From the result of this test, I think it can not be denied that the absorption by a vapor measured by Tyndall is genuine. Lecher and Pernter have also been measuring an effect which depends on the amount of vapor

*Lecher and Pernter say: "x always becomes *smaller* as the thickness of the layer becomes smaller," which is obviously erroneous.

present, and where their results deviate from those of Tyndall it is owing to the defects of their method. It seems to me that the capacity of lampblack for condensing vapors to the liquid state, and absorbing them in its pores, is partly* responsible for the apparent inactivity of aqueous vapor in Lecher and Pernter's experiments by the compensation already explained; and it is noteworthy that their deviations from Tyndall are greatest in the case of the more condensible vapors, while for the permanent gases there is approximate agreement, especially if the comparison be made between the absorption of equal masses† exercised on radiation from the same source. This has been done in the last column of Table 53 for the three permanent gases by interpolating values, for a pressure of 7.5 inches of mercury, from Tyndall's *Contributions to Molecular Physics*, Table XX, p. 37, for CO_2, and Table I, p. 22, for C_2H_4, assuming that the total radiation is represented by the mean of the values on pages 18 and 19, or 334 units.‡ The figures for CO are obtained in the same way from Table XIX, p. 36. The pressure selected§ is such as to give an absorbent mass nearly identical with that of Lecher and Pernter. The result indicates that, where the physical state remains unchanged, it is permissible to compare the effects of equivalent masses even under diverse conditions of pressure or, in other words, it is the number of molecules encountered in passing through a given gas which determines the absorption of radiation.

From certain discrepancies in the relative positions of absorbent vapors in Tyndall's lists Lecher and Pernter deduce a variation of some 30 per cent. between the results from black and from polished tubes, and conclude that the unconformities which Tyndall attributed to impurities in his substances are really due to the variable proportion in which the transmission through a film of liquid adhering to the walls and the direct transmission through vapor enter into the results, according as a reflecting or a nonreflecting tube is employed. The criticism, however, is hardly conclusive, especially since they found their remarks on some of Tyndall's earlier measures in which the probable error of observation was large.

Finally, while themselves recognizing that transmission must be expressed by an exponential formula,

$$t = e^{-mx}$$

in which, unless the radiation be homogeneous, x varies as a complex function of m (the absorbent mass), any constant exponential coefficient being inapplicable to cases of absorption where particular rays are constantly dropping out, because totally extinguished, the authors fail to apply their knowledge where it is peculiarly needed, namely, in treating Violle's comparison of solar radiation at the top and bottom of Mount Blanc. They rightly conclude that the absorption of 16 per cent. exercised on the solar rays by a layer equivalent to 2,428 meters of air at normal pressure, and having a pressure of water-vapor of 5.3 mm. at the bottom, must have been largely due to the aqueous absorption; but, applying an erroneous formula, they then deduce a mean

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* It is evident that if the explanation given here is correct the numerical result must also depend in part upon the dimensions of the apparatus.

† Tyndall (*Heat as a Mode of Motion*, p. 433–435) has given an argument which proves that equivalent absorbing masses must be used, if the relative absorptions of different liquids and vapors are to be compared.

‡ From the explanation of the calibration of the galvanometer (pp. 17–19), and from the values juxtaposed in Tyndall's Tables I, III, and elsewhere, it is evident that the quantities labeled "absorption per 100" are not percentages, but absorptions stated in terms of forces, corresponding to galvanometer deflections, as read from a curve of calibration.

§ The values for the interpolation curve, in the case of carbon dioxide (4-foot layer, temperature of source 100° C., *loc. cit.*, p. 15), follow :

Pressure.	Absorption (obs.).	Absorption (interpolated).	Pressure.	Absorption (obs.).	Absorption (interpolated).
Inches.	*Per cent.*	*Per cent.*	*Inches.*	*Per cent.*	*Per cent.*
0.5	1.50	1.8	3.0	6.53	5.8
1.0	2.25	3.0	3.5	7.34	6.3
1.5	3.14	3.8	5.0	7.49	7.8
2.0	4.19	4.5	10.0	10.78	11.3
2.5	5.33	5.2	15.0	14.37	13.9

absorption of 0.007 per cent. by 1 meter of air of the given humidity and for sunshine, and compare this with Tyndall's absorption of radiation from a low-temperature source by a fresh layer of moist air, leaving the inference that this measurement—several hundred times greater than that computed on their assumption—must necessarily be wrong. This reasoning is quite inadmissible. In sunshine the rays absorbable by water form but a small part of the total radiation, while in the low-temperature sources employed by Tyndall they constitute the larger part. Besides this, the principal part of the absorption is exercised by the first few meters of moist air or their equivalent. It is perfectly safe to say that even at the summit of Mount Blanc an amount of aqueous vapor had already been traversed many times exceeding that in Tyndall's meter or thereabouts of moist air, and that a large part of the rays for which aqueous vapor is especially opaque and whose absorption was measured by Tyndall had already been sifted out. The reasoning by which Professors Lecher and Pernter support their failure to detect any absorption from moist air is, therefore, not justified.

Tyndall's last contribution to this subject is a paper on "The action of free molecules on radiant heat and its conversion thereby into sound" (*Phil. Mag.* (5), vol. 13, pp. 435–462, and 480–526, May and June, 1882). It contains a variety of incidental results which have a bearing on questions which have arisen in connection with the present research. The beginning of the paper gives an excellent historical summary of the Tyndall-Magnus controversy. On pages 455–456 we read concerning Magnus' experimental determination of the radiation from heated gases passed through a hot tube 15 mm. in diameter, bent up at the end, so that the vertical current ascended 400 mm. in front of the pile:

> When dry air was sent through this tube the deflection produced was three divisions of a scale; when air which had passed through water at a temperature of 15° C. was sent through the tube the deflection rose to 5 div.; when the water was warmed to 60° or 80° F. the deflection was 20 div.; and when the water boiled the deflection was 100 div. In this last experiment, however, a mist appeared, so that, as urged at the time, the radiation could not be said to have been purely from vapor. In the other case no mist was visible, but it was nevertheless concluded that the 20-div. deflection was due to the formation of mist at the boundary of the ascending current.

Tyndall concludes that the first deflection came—

> Not from dry air, but from the adjacent aqueous vapor which had been warmed by the dry air.
>
> That the deflection in the second experiment was small is not surprising. The radiation which could reach the pile from a jet of air only 15 mm. in diameter, and containing such moisture as could be taken up at 15° C., must have been extremely small under any circumstances. But in the present case even this small radiation was diminished by the passage of the [radiant] heat through 400 mm. of undried air. I should demur [says Tyndall] to the explanation of the third experiment and question the warrant to imagine a mist which could not be seen. Even the fourth experiment where mist was visible, yielded, I doubt not, a mixed result, part of the effect, and probably the smallest part, being due to the mist, and part of it to the vapor.

On pages 483–484 Tyndall refers to his own experiments on the transmission of a parallel beam of radiation from a rock-salt lens, described in his *Contributions* (p. 394), and says that the tube was rough brass, tarnished, and that the heating of the tube from air dynamically heated by compression, and from the partial condensation of vapor on the walls of the tube when the air was moist, produced a small radiation from its inner surface which disturbed the result. Hence in his new apparatus the interior of the tube was silvered and polished.

The absorptions measured by Tyndall are greater when the source is a slowly vibrating or low-temperature one, except in the case of absorption by carbon dioxide; but if the apparatus could be made sensitive enough to work with a very low-temperature source of radiation whose spectral maximum should be at a longer wave-length than the region of especial absorption, the result found for carbon dioxide would, no doubt, be the general one.

The radiation from a hydrogen flame proceeds principally from highly heated vapor of water and its absorption by 38 inches (96.5 cm.) of air at 60° F., saturated with moisture and containing an amount of water-vapor equivalent to a liquid layer 0.001 271 cm. deep, was found to be 10.7 per cent., while dry air produced no measurable absorption.

The thin liquid films produced by condensation of vapors on rock-salt plates when the concentrated vapors were allowed to flow over a plate placed in the path of the radiant beam were found to have no effect on transmission, unless, as in breathing on a plate, the film amounted to a

visible wetting; but if the plate was put in contact with the pile the liberation of latent heat in the act of condensing from vapor to liquid produced powerful deflections.

The assumption that absorption depends upon the mass of the absorbent material traversed by the rays, and therefore is constant if the density of a vapor varies inversely as its depth, has appeared probable. To test the assumption further, Tyndall had two tubes whose lengths were as 3.5 to 1 and measured the percentage absorptions of ether-vapor, $(C_2H_5)_2O$, at inverse pressures.

Table 55.

Radiant source.	Inches.	Inches.		Per cent.
A dull lime light	l_1=38.0 l_2=10.8	p_1=1.0 p_2=3.5	lp 38	a=30.3 30.0
	38.0 10.8	2.0 7.0	lp 76	38.8 38.5
Brighter lime light	38.0 10.8	1.0 3.5	lp 38	22.3 22.5
	38.0 10.8	2.0 7.0	lp 76	29.5 30.0
Brightest lime light	38.0 10.8	1.0 3.5	lp 38	18.4 18.8
	38.0 10.8	2.0 7.0	lp 76	25.7 25.6

The assumption of constant absorption of radiation from a source of constant temperature by an absorbent of constant mass is verified in this case, the physical state remaining unchanged.

The question whether the absorption of a given mass of material will remain constant when its state changes from the liquid to the vaporous condition demands separate treatment. Tyndall's answer for ethyl ether is contained in the following paired values:

Radiant source.		Absorption. Per cent.
Lime light with mirror	Ether vapor " liquid	32.4 32.9
" " " rock-salt lens	" vapor " liquid	33.3 33.3
Incandescent platinum with rock-salt lens	" vapor " liquid	66.7 67.2
The same on another occasion	" vapor " liquid	71.0 70.0

In like manner hydride of amyl (source of radiation not stated) gave equal absorptions of 51 per cent. in the two states. It is, of course, impossible to assert from these few observations that a like identity of liquid and vaporous absorption will hold good for other substances, although Tyndall's opinion was to the contrary,* and I shall show later that it does not hold true for water.

The experiments which give the title to the paper and introduce a novel method follow. By interrupting a convergent beam concentrated on a small bulb containing a vapor, employing for this purpose a toothed wheel revolved with such rapidity as to give the number of pulsations which evoked the resonance of the bulb, Tyndall found that the heat, instantaneously absorbed and radiated by the vapor, produced alternate expansion and contraction, giving a musical note whose intensity was proportioned to the combined absorbent and radiative power, as well as to the difficulty with which the substance volatilizes. The expansion could also be made evident upon a manometer. When radiation from a lime light was concentrated by a mirror upon a cylin-

* In regard to the equality of liquid and vaporous absorption Tyndall says (p. 500): "A general law of molecular physics is, I apprehend, here illustrated."

drical vessel 4 inches long and 3 inches wide, with rock-salt end plates, the following water pressures were obtained on the manometer, according to the contents of the vessel:

	mm.
Chloroform, CH_3Cl	350
Aldehyde, C_2H_4O	325
Olefiant gas, C_2H_4	315
Ethyl ether, $(C_2H_5)_2O$	300
Nitrous oxide, N_2O	198
Marsh gas, CH_4	164
Carbon dioxide, CO_2	144
Carbon monoxide, CO	116
Oxygen, O_2	5
Hydrogen, H_2	5
Nitrogen, N_2	5
Dry air	5
Humid air, at 50° C	130

Although a few of the more absorbent of these substances, such as nitrous oxide and marsh gas, may exist as barely perceptible traces in the Earth's atmosphere, and carbon dioxide in larger proportion, the interest of this series to the meteorologist of course centers in the absorption of moist air relatively to that of dry air. The numbers, however, do not coincide with the relative absorbent values, being modified by the radiant powers of the substances, but as it is precisely this combination of radiative and absorbent qualities which determines the thermal state of the atmosphere, these relations are significant. In alluding to their meteorological bearing Professor Tyndall remarks (p. 516):

The radiant power of air being practically *nil*, it retains for a considerable time the warmth imparted to it during the day, while when it is dry the rays from the surface of the earth pass unimpeded through it. Hence the relative refrigeration of the surface [at night and in dry weather].

The radiant power of dry air is underrated by Tyndall here and elsewhere,* but the general accuracy of his analysis of the atmospheric thermal mechanism remains unimpaired.

If the exact equivalence in absorption by equal masses of a substance in the liquid and in the vaporous states had been as firmly established as Tyndall imagined, his measures of the absorption of liquid water (*Heat as a Mode of Motion*, p. 430) could be utilized in connection with the atmospheric problem. The observations, which were made on radiation from a plantinum spiral raised to a bright red heat by an electric current, follow:

Table 56.

Thickness of liquid water.		Absorption.
Inches.	*cm.*	*Per cent.*
0.02	0.05	80.7
0.04	0.10	86.1
0.07	0.18	88.8
0.14	0.36	91.0
0.27	0.69	91.0

For comparison of absorption by water in the vaporous condition, the following values of the absorption by an air column, nearly 100 meters long, with varying humidity, have been taken from a treatise on the Moon's radiation, which includes some subsidiary researches on atmospheric absorption ("The Temperature of the Moon, from researches made at the Allegheny Observatory," by S. P. Langley, assisted by F. W. Very. *National Acad. of Sci.*, vol. 4, part 2, 3d Memoir, p. 186, Washington, 1889). In the last column I have deducted 2.5 per cent. from the original numbers for the absorption of carbon dioxide.

* The small expansions of dry air and its chief constituents, nitrogen and oxygen, are attributed by Tyndall to a warming of the apparatus and to expansion of the gas by heat communicated to it by convection, rather than to heating by direct absorption of radiation by the gas; but, as in the case of dynamic heating, no sufficient reason is given for rejecting these smallest readings.

TABLE 57.

Relative humidity.	Equivalent depth of liquid water.	Absorption.
Per cent.	*cm.*	*Per cent.*
53	0.096	12.1
60	0.151	19.3
61.5	0.166	21.8
82	0.205	30.4

Plotting the observations with depths of precipitable water for abscissæ and absorptions for ordinates, it will be seen that the curve (fig. 13) departs slightly from a straight line, and more as

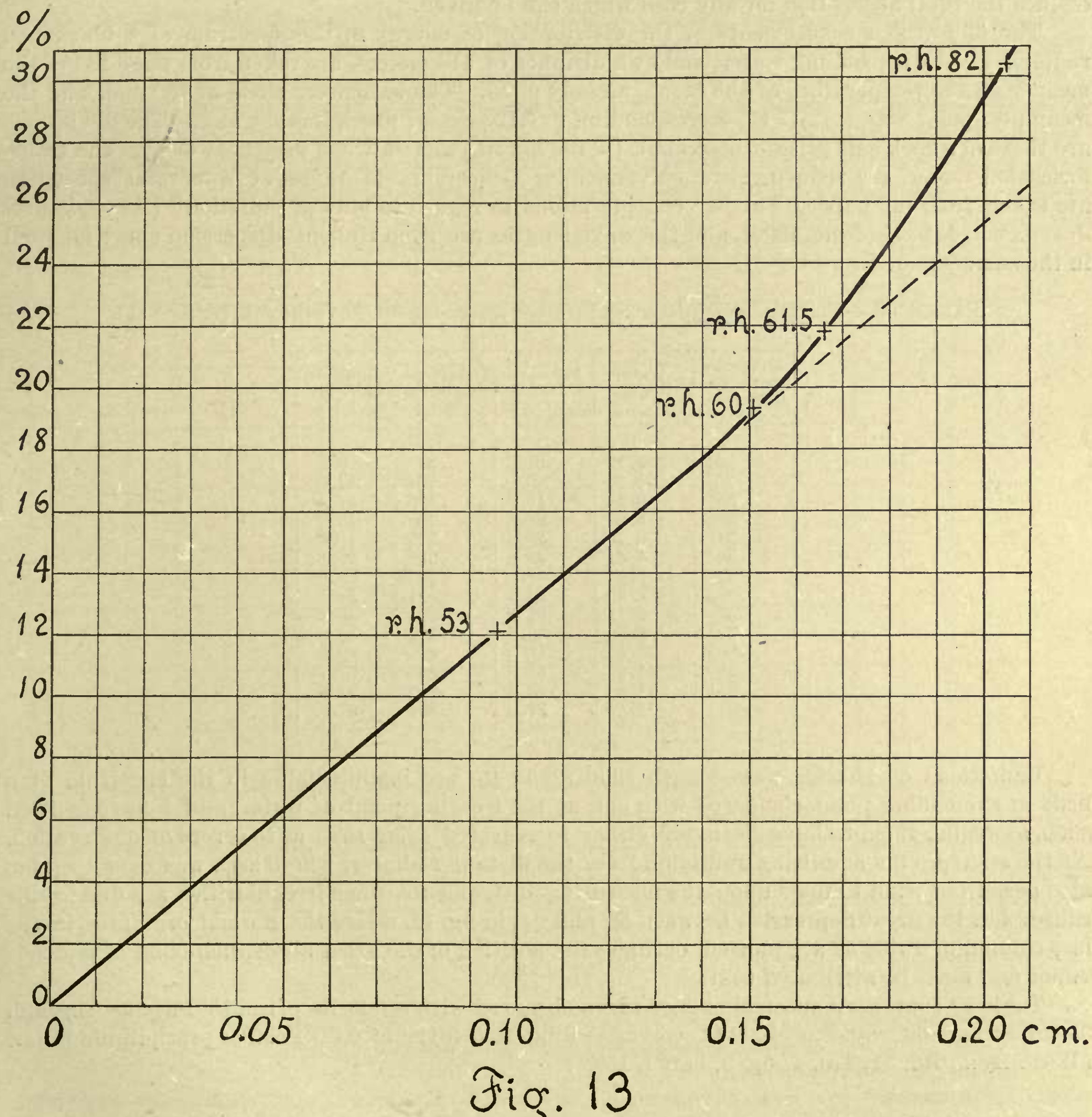


Fig. 13

the relative humidity increases, at least for relative humidities above 60 per cent. I infer that for an equivalent depth of 0.2 cm. of liquid water, for which an absorption of 28.8 per cent. is indicated,

a reduction of 3.6 per cent. should be made to allow for an increment of absorption dependent upon greater relative humidity, the remaining absorption of 25.2 per cent. being due to normal water-vapor, plus an unknown but evidently very small correction for the effect of dry air.

For the equivalent depth of 0.18 cm. the absorption of water-vapor is 22.6 per cent., which may be compared with Tyndall's third observation (Table 56), whence it appears that for this amount of water the liquid absorption is four times the vaporous; but the râte of absorptive increase with growing depth is very different for the two states, and for an equivalent depth of one-half millimeter we have vaporous aqueous absorption, 6.2 per cent.; liquid aqueous absorption, 80.7 per cent., the liquid absorption being thirteen times greater than the vaporous.

No allowance is made here for any change produced by differences in the radiant source; but I shall now develop a method by which we may be independent of the temperature of the source. By combining spectral energy-curves and curves of absorption for homogeneous rays, we may deduce the total absorption for any case which can be given.

The following measurements of the distribution of energy in the spectrum of a blackened radiator filled with boiling water, and at a distance of 110 meters, are taken from page 186 of the memoir on the temperature of the Moon, already cited. The barometer stood at 739 mm., and the mean dew-point was + 12°.7 C., corresponding to 0.122 cm. of precipitable water. The deviations are those of a rock-salt prism whose angle (p. 132 *loc. cit.*) was "always very near 60°." The transformation factor, for reducing the galvanometer deflections to those of a normal spectrum, are taken from my paper "Further considerations in regard to laws of radiation" (*Astrophysical Journ.*, vol. 4, p. 43, June, 1896), and the wave-lengths are from Rubens' dispersion curve adopted in the same paper.

TABLE 58.—*Spectral energy-curves through water-vapor* (*radiant source, 99° C.*).

Minimum deviation (rock-salt.)	Wave-length.	Prismatic deflection.	Transformation factor.	Normal deflection.
°	μ			
39¼	3.10	31.3	.305	9.5
39	4.26	40.0	.364	14.6
38¾	5.22	48.8	.432	21.1
38½	6.03	28.4	.491	13.9
38¼	6.76	30.2	.549	16.6
38	7.41	42.6	.599	25.5
37¾	8.01	52.0	.647	33.6
37½	8.59	55.7	.691	38.5
37¼	9.11	62.0	.733	45.4
37	9.60	50.0	.772	38.6
36½	10.45	48.0	.839	40.3
36	11.2	42.0	.898	37.7
35½	11.85	33.2	.949	31.5
35	12.4	27.2	.991	27.0

Radiations of shorter wave-length than about 2μ are inappreciable in the spectrum of a body at the boiling point compared with one at the freezing point of water, and I have omitted such, assuming them to have been due either to reflected solar rays or to errors of observation. As the aperture for admitting radiation from the distant radiator, whose area was over 1 sq. m., also permitted wind to blow upon the measuring instruments, some irregularities are due to this cause; but the great depression between 5μ and 9μ, in fig. 14, where the normal ordinates in the last column of Table 58 are plotted, occupies the position of the great absorption-band of aqueous vapor and must be attributed to it.

Table 59 contains a spectral energy-curve observed with a fluorite prism by Paschen through 33 cm. of aqueous vapor at 100° C., corresponding to a layer of 0.0194 cm. of precipitable water. (*Wied. Ann.*, Bd. 51, Taf. 1, fig. 3, heft 1, 1894.)

TABLE 59.—*Absorption by steam.*

Minimum deviation (fluorite).	Wave-length.	Radiation unabsorbed.	Radiation after absorption.	Transmission.	Absorption.
° ′	μ			*Per cent.*	*Per cent.*
28 46.5	5	99	74	74.7	25.3
28 16	5.5	76	16	21.1	78.9
27 41.5	6	56	5	9.0	91.0
27 5.5	6.5	41	3	7.3	92.7
26 25.5	7	30.5	6	19.7	80.3
25 40	7.5	21	15	71.4	28.6
24 52	8	14.5	13.5	93.1	6.9
24 1	8.5	7.5	7.5	100	0

The measured radiations are not given in this paper, and the values, corresponding to ether-waves differing in length by half a micron, have been read from the curves. The source of radiation was a hot sheet-iron cylinder over an Argand burner. The absorbent vapor was contained in a cylindrical metal tube 4 or 5 cm. in diameter, closed by end plates of thinnest copper, in which were open slits "of such dimensions that no rays reflected from the inner walls of the tube could reach the bolometer, but only such radiation as had passed directly through the gas layer in the tube. In this way all disturbance by 'adhesion of vapor,' etc., was excluded. A slender

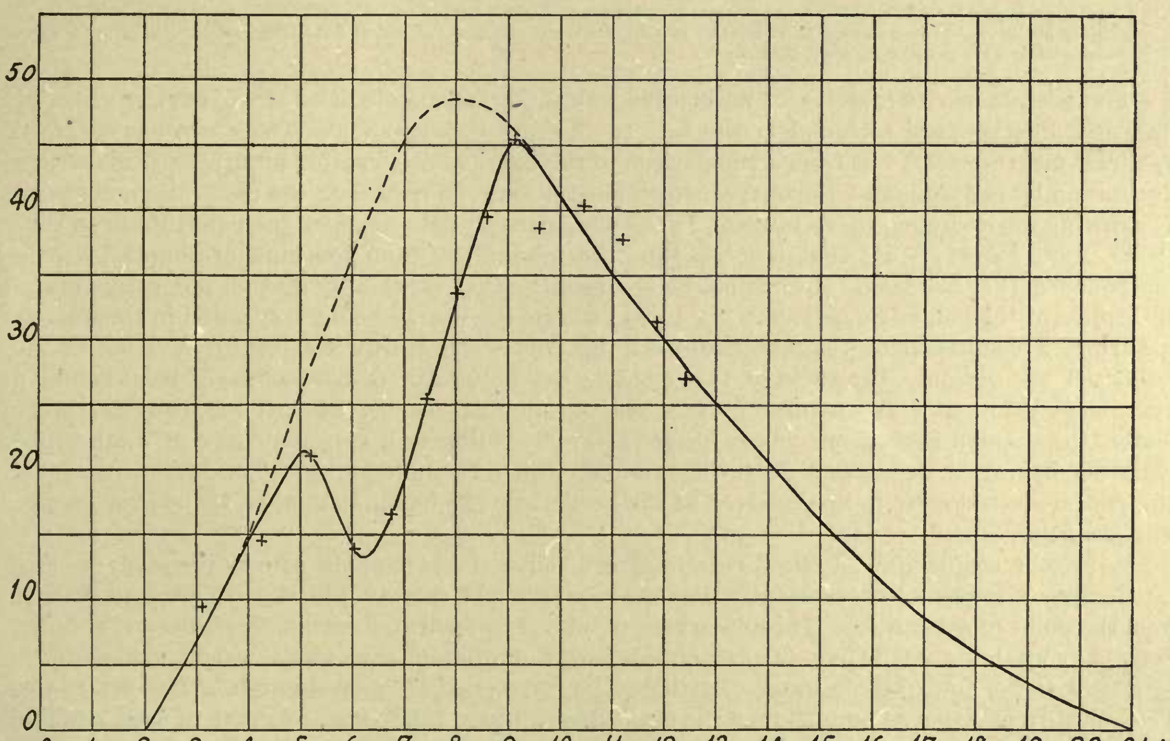


Fig. 14

Great water-vapor absorption-band. (Equivalent liquid = 0.122 cm.). Energy-curve of normal spectrum, reduced from rock-salt prismatic spectrum.

metal tube was screwed into the middle of the tube. This served to convey the gas under investigation in a slow but steady stream through the tube. In this way there was interposed a flowing layer of gas, of dimensions not exactly known, but very constant." (*Loc. cit.*, p. 4.) These measures are not available to as great wave-lengths as those made with a rock-salt prism, because

the absorption of fluorite nearly obliterates the radiation in the extreme infra-red spectrum where water-vapor begins to recover transmissive power.

Completing the missing portion of the energy-curve in fig. 14, as in the upper broken line, by the aid of spectral measures on a near radiator at the same temperature in dry weather, and adjusting the areas so as to give the same absorption (15.3 per cent.) which the curve in fig. 13 indicates for a depth of 0.122 cm. of precipitable water, the following radiant energies and percentages of absorption are obtained:

TABLE 60.—*Absorption by aqueous vapor.*

Wave-length.	Radiation unabsorbed.	Radiation after absorption.	Percentage transmitted.	Absorption. 0.1220 cm.*	Absorption. 0.0194 cm.†	Absorption. 0.0041 cm.‡
μ				*Per cent.*	*Per cent.*	*Per cent.*
5	26.0	21.3	81.9	18.1	25.3	5
5.5	31.2	19.0	60.9	39.1	78.9	40
6	36.4	14.0	38.5	61.5	91.0	68
6.5	41.6	14.0	33.7	66.3	92.7	70
7	45.6	20.0	43.9	56.1	80.3	47
7.5	48.0	26.8	55.8	44.2	28.6	20
8	48.5	32.2	66.4	33.6	7.9	14
8.5	47.6	39.2	82.4	17.6	0	5 (?)

* Absorption by water vapor in 110 meters of air at ordinary summer temperature, equivalent to 0.1220 cm. of liquid water.
† Absorption by 33 cm. of steam at 100° C., equivalent to 0.0194 cm. of liquid water. (Paschen, *Wied. Ann.*, as above, Table 59.)
‡ Absorption by 7 cm. of steam at 100° C., equivalent to 0.0041 cm. of liquid water. (Paschen, *Wied. Ann.*, Bd. 52, Taf. II, fig. 1, curve 1 *c*, in which ordinates are percentages of absorption.)

For comparison two series of absorption values for steam, deduced from curves given by Professor Paschen, are included in the last two columns of Table 60. These are not obtained by direct measurement, but from a comparison of the curve of observation after absorption with a restoration by estimation of the curve before absorption. In regard to the restoration, obtained by drawing a continuous curve tangent to the shoulders on either side of the band, Paschen says (*Wied. Ann.*, Bd. 51, S. 11) that it "has thus too low rather than too high ordinates," and in consequence the indicated absorption is too small. This especially affects the estimates of absorption of the longer waves from 7.5 μ to 9 μ, where, the energy being very small in the fluorite spectrum, a comparatively slight change in the curve will produce a large alteration in the estimated absorption. The effect of this error is less noticeable with a source of radiation at a high temperature, such as was used by Paschen, but applied to observations on a low-temperature source, these small absorption values from 7.5 μ to 9 μ will give a restored curve of unabsorbed radiation having a depression at the maximum, which is inadmissible. The larger values of absorption are therefore to be preferred at the borders of the band, at least on the side of greater wave-length.

A further comparison of these results shows that a short column of concentrated, or saturated vapor absorbs more powerfully than an equal amount largely diluted with air, and further from the point of saturation. The absorption of a layer of saturated steam, 7 cm. deep (Table 60, Series 3) containing 0.0041 cm. of precipitable water, undiluted, exercises as great an absorption as 0.1220 cm. of precipitable water distributed as unsaturated vapor through 11,000 cm. of air. The quantity of vapor is here 30 times as great, the dilution 1,571 times as great in case 1 (Table 60) as in case 3. I have shown, however, that in the free air, where the dilutions are not widely different, the absorption is nearly proportional to the vapor contents, at least up to a depth of 100 meters.

A more extensive comparison may be made. I have found that a layer of water, 40 cm. thick, is almost absolutely impervious to solar infra-red radiation beyond wave-length 1.0 μ. No such absorption occurs with the most humid air as the sun approaches the horizon, although the absolute amount of water in a vaporous form, interposed in the path of the rays, must often be even greater than that contained in a liquid layer 40 cm. thick. Hence from the result of this test, made for us in nature on a grand scale, we have conclusive evidence that the selective absorption of vaporous water is not identical with that of liquid water, but that the former is comparatively

permeable to infra-red radiations. Nevertheless, the general form of the absorption curve in the infra-red spectrum, as to its coarsest details, or broad groups of absorption-bands, and their relative intensities is very similar in the two cases.

Passing to the absorption-spectrum of liquid water, I have measured the ordinates in the spectral energy-curves for a fluorite prism which Paschen has given (*Wied Ann.*, Bd. 52, 1894, Taf. II, fig. 2, curves 1 to 4), in which a blackened platinum strip at 450° C.* was the radiant source. These readings have been divided by the ordinates with empty cell to obtain the corresponding percentage transmissions which are given in the next table.

TABLE 61.—*Absorption by liquid water.*

	Wave-length.	2μ	2.5μ	3μ	3.5μ	4μ	4.5μ	5μ	5.5μ	6μ	6.5μ	7μ	7.5μ	8μ	8.5μ
	Min. deviation . .	30°47′	30°34′	30°18′	29°59′	29°38′	29°14′	28°47′	28°16′	27°42′	27°6′	26°26′	25°40′	24°52′	24°1′
	WATER. *cm.*														
Radiation.	0.0000	374	507	607	556	443	339	262	194	133	101	86	63	38	18
	0.0015	350	373	58	397	318	244	193	146	45	64	60	42	28	16
	0.0030	340	330	6	317	298	135	135	92	5	15	18	14	9	6
	0.0080	305	135	2	137	147	21	33	23	2					
Transmission.	.0015	93.6	73.6	9.6	71.4	71.8	72.0	73.7	75.3	33.8	63.4	69.8	66.7	73.7	88.9
	.0030	90.9	65.1	1.0	57.0	67.3	39.8	51.5	47.4	3.8	14.9	20.9	22.2	23.7	33.3
	.0080	81.6	26.6	0.3	24.6	33.2	6.2	12.6	11.9	1.5					
Absorption.	.0015	6.4	26.4	90.4	28.6	28.2	28.0	26.3	24.7	66.2	36.6	30.2	33.3	26.3	11.1
	.0030	9.1	34.9	99.0	43.0	32.7	60.2	48.5	52.6	96.2	85.1	79.1	77.8	76.3	66.7
	.0080	18.4	73.4	99.7	75.4	66.8	93.8	87.4	88.1	98.5					

The transmissions in this table, for the longer wave-lengths, have been multiplied by the ordinates of an unabsorbed normal spectral energy-curve at 100° C. to obtain the figures in the last three lines of Table 62, and the curves in fig. 15.

TABLE 62.—*Spectral energy-curves through liquid water (radiant source 100° C.).*

Wave-length.	5μ	5.5μ	6μ	6.5μ	7μ	7.5μ	8μ	8.5μ
WATER. *cm.*								
(1) 0.0000	26.0	31.2	36.4	41.6	45.6	48.0	48.5	47.6
(2) 0.0015	19.2	23.5	12.3	26.4	31.8	32.0	35.7	42.3
(3) 0.0030	13.4	14.8	1.4	6.2	9.5	10.7	11.5	15.2
(4) 0.0080	3.3	3.7	0.5	[0.5]	[2.2]	[2.8]	[1.0]	[2.0]

Measures made with a fluorite prism are not available for wave-lengths longer than 9 μ where the absorption of fluorite becomes large, but after this point aqueous absorption is comparatively insignificant until the region of the spectrum beyond 13 μ is reached. Solar and lunar radiations longer than 9 μ penetrate our atmosphere freely, even in moist summer weather, and Tyndall's observations (quoted in Table 56) show that 9 per cent. of the rays from platinum at a bright-red heat resist the absorption of liquid water. This remnant is distributed at irregular intervals through the spectrum. As the region beyond 12.5 μ comprises but a small fraction of the total energy from such a source, I shall assume, merely for the present purpose, that aqueous absorption ends at 12.5 μ, and as it is probable that certain feeble atmospheric absorption bands of

*Subsequent measures by Paschen have indicated that the unabsorbed maximum in this curve has been displaced toward the shorter wave-lengths, owing to the imperfect absorption of the long waves by the bolometer, and that the maximum should be at 4 μ.

greater wave-length than 9 μ are due to water-vapor, the curves are drawn undulating in the dotted portions supplied to complete the areas. The spectral region between 9 μ and 12 μ is very readily transmitted by water-vapor, but the limits of liquid absorption are wider. Aqueous

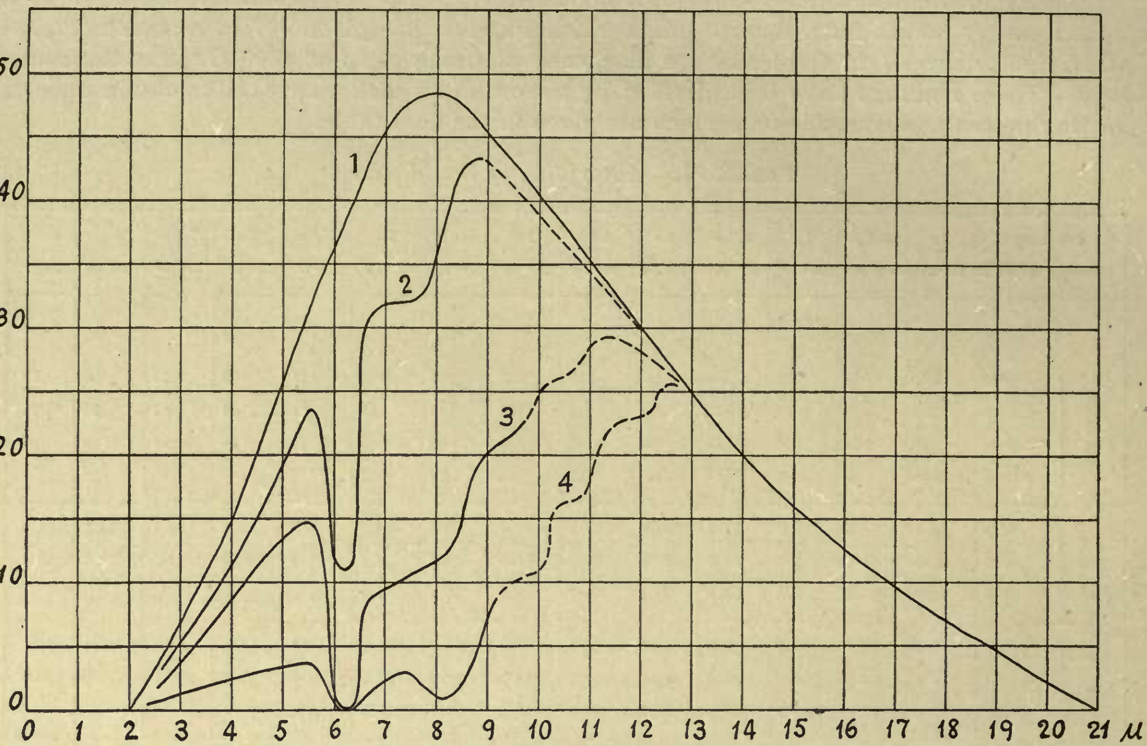


Fig. 15

Energy-curves of normal spectrum after absorption by liquid water.

absorption increases again gradually beyond 12 μ, and is perhaps the cause of the practical ending of the spectrum near 20 μ.

Measuring the areas of the curves in fig. 15, and comparing 2, 3, and 4 successively with the unabsorbed energy-curve (1), the following transmissions of total radiation from a source at 100° C. are obtained:

TABLE 63.

Depth of liquid water.	Area of spectral energy curve.	Transmission of total radiation.	Absorption of total radiation.
cm.		*Per cent.*	*Per cent.*
(1) 0.0000	1.420	100.0	0
(2) 0.0015	1.016	71.5	28.5
(3) 0.0030	0.630	44.4	55.6
(4) 0.0080	0.341	24.0	76.0

If the aqueous absorption is exercised on radiation from a red-hot source, wave-lengths from 2μ to 5μ must be included, which is done in Table 64, the transmissions being obtained from Table 61, and combined with radiant values from a normal spectral energy-curve, taken from the reduction for a source estimated at 815° C., given in my paper, "Further considerations concerning laws of radiation" (*Astrophysical Journ.*, vol. 4, p. 43), in which, however, the temperature has probably been placed too high, since the position of the unabsorbed maximum more nearly agrees with that of the ideal black body at 450° C. (see footnote, p. 95; compare also my note in *Astroph. Journ.*, vol. 10, p. 208, Oct., 1899); but the discrepancy may arise in part from the use in the present case of a radiant which is not an ideal black body.

TABLE 64.—*Spectral energy-curves through liquid water (radiant source 815° C. ?).*

Wave-length.	2μ	2.5μ	3μ	3.5μ	4μ	4.5μ	5μ	6μ	7μ	8μ	9μ	10μ	15μ	20μ
WATER.														
cm.														
(1) 0.0000	40	67	160	187	193	190	182	154	117	84	60	42	16	5
(2) 0.0015	37.4	49.3	15.4	133.5	138.6	136.8	134.1	52.1	81.7	61.9				
(3) 0.0030	36.4	43.6	1.6	106.6	129.9	75.6	93.7	5.9	24.5	19.9				
(4) 0.0080	32.6	17.8	0.5	46.0	64.3	11.8	22.9	2.3						

These values are plotted in fig. 16. Three principal regions of large absorption are shown. The first, extending from 2.2μ to 3.7μ, with the minimum near 3μ, occupies the position of Langley's X and associated bands (χ_1 χ_2) in the solar spectrum. The second depression from 4.2μ to 5.2μ (minimum at 4.7μ) encroaches on the great carbon dioxide band, but does not seem to be as

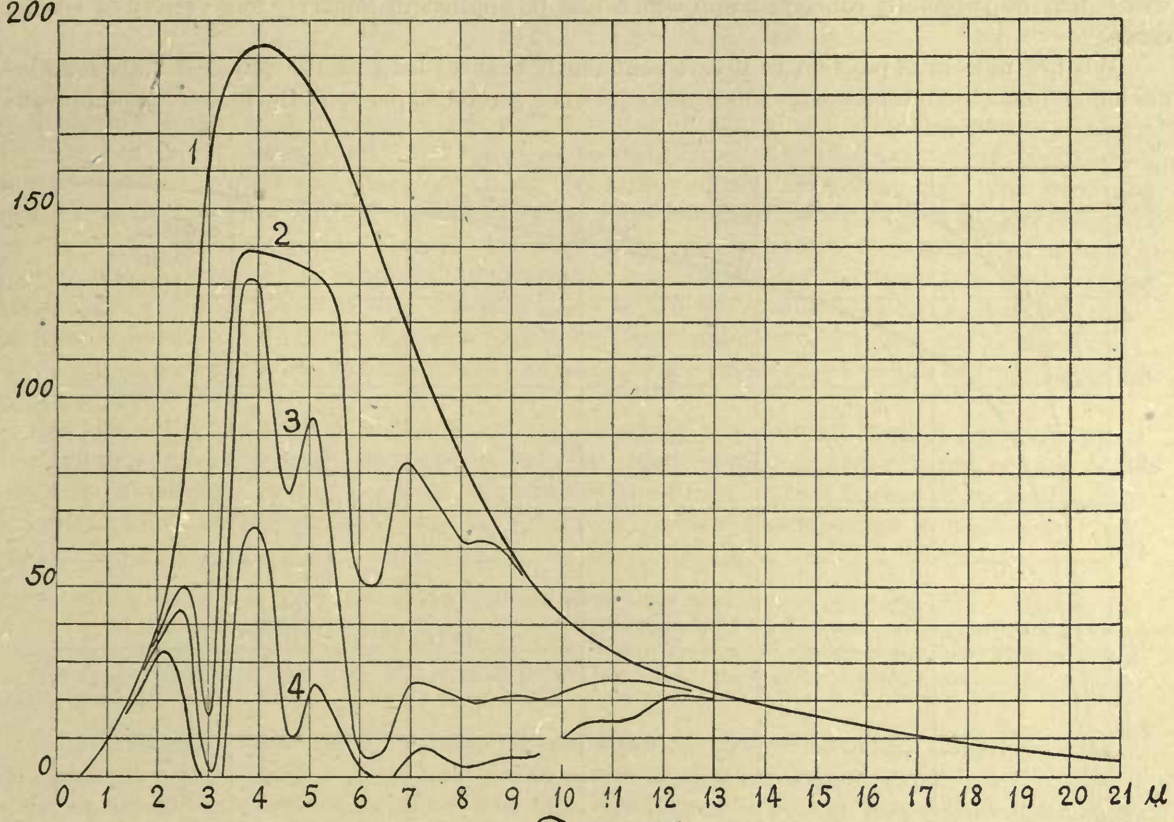


Fig. 16

Energy-curves of normal spectrum after absorption by liquid water.

strongly developed in the vaporous absorption of water; neither does it appear in the absorption of 0.0015 cm. of liquid water, although quite well marked in the curve for 0.0030 cm. The third region is that of the great aqueous absorption band from 5.2μ to 7.0μ with a subordinate extension to 9μ, its deepest depression being at 6.1μ. The vaporous absorption differs in showing two minima, at 5.86μ and 6.51μ. A succession of smaller bands follows, the absorption of the liquid diminishing from 8μ to 12μ. In this region aqueous vapor has very free transmission, and the same is true of a liquid layer 0.0015 cm. thick.

Comparing areas in fig. 16 the following transmissions of total radiation from a source estimated at 815° C. are found:

TABLE 65.

Depth of liquid water.		Area of spectral energy curve.	Transmission of total radiation.	Absorption of total radiation.
	cm.		*Per cent.*	*Per cent.*
(1)	0.0000	2.576	100	0
(2)	0.0015	2.175	84.4	15.6
(3)	0.0030	1.487	57.7	42.3
(4)	0.0080	1.015	39.4	60.6

Within the given limits of temperature (100° and 815° C.) the transmission for every thickness is greatest for the radiation from the hotter source, a result which is as old as the measurements of Melloni, but which is here presented no longer as an empirical fact, but as a piece of knowledge which may be rationally conceived and which can be applied deductively to a variety of special cases.

We are now in a position to assert confidently that so long as the physical state remains unchanged and the total aqueous absorption does not exceed 50 per cent. the increment of aqueous

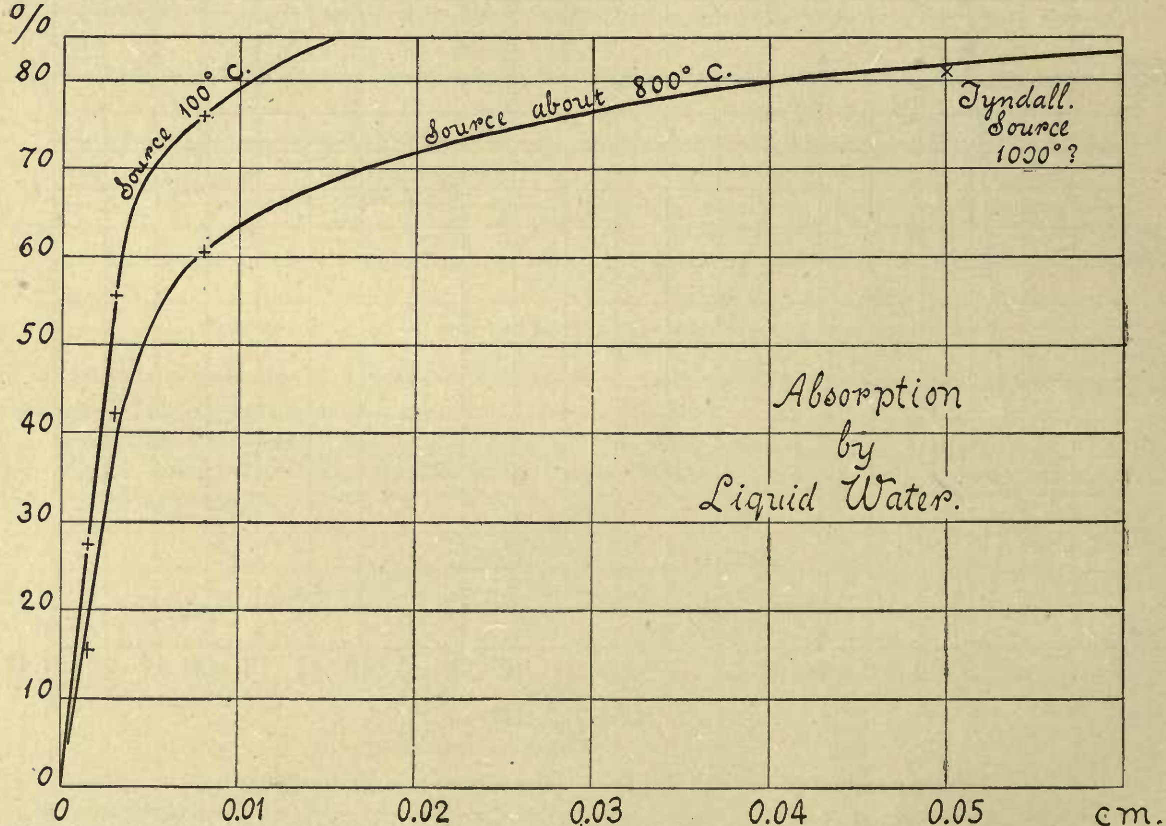


Fig. 17

absorption is nearly proportional to the depth of the absorbing layer, but beyond this point the rate of increase in the absorption falls off very rapidly until finally further addition to the layer produces almost no effect.

Next, by comparing the curves in figs. 13 and 17, it can be stated that the absorption of total

radiation by water-vapor in high dilution in the free air falls far below its absorption when condensed to the liquid state, but in a ratio which varies with the depth of the absorbent mass, as the following table shows:

TABLE 66.—*Aqueous absorption of total radiation (radiating body at 100°).*

Depth of precipitable water.	Absorption by liquid water.	Absorption by vapor in 100 m. air.	Ratio liquid absorpⁿ / vapor absorpⁿ.
cm.	*Per cent.*		
.001	19.5	0.125	156
.002	38.0	0.250	152
.003	55.5	0.375	148
.004	63.3	0.500	127
.005	67.9	0.625	109
.006	71.2	0.750	95
.007	73.8	0.875	84
.008	76.0	1.000	76
.009	78.0	1.125	69
.010	79.8	1.250	64

From this comparison it appears that with a radiating source at the boiling point of water, 10 microns of liquid water absorb 156 times as powerfully as the same amount of water distributed in the vaporous state through about 100 meters of air. We have seen that even an approach of the aqueous vapor to its condensation point increases its absorptive power (Table 57 and fig. 13). Paschen's result, already described (*ante*, p. 94), shows that saturated aqueous vapor at 100° C. exercises an intermediate absorption between that of the liquid and the invisible nonsaturated vapor of the atmosphere, 40 microns of liquid water absorbing 63 per cent. of radiation from a source at 100° C. (by Table 66), while the same quantity of water in the form of steam takes out about 15 per cent., and distributed as atmospheric vapor only one-half of 1 per cent. (by fig. 13 and Table 66).

The identity of absorption in the liquid and vaporous states which Tyndall found for ethyl ether and amyl hydride, presumably obtains only for those substances which do not change their molecular constitution in passing from one state to the other. The influence of molecular form upon absorption was, indeed, recognized by Tyndall, who says (*Contributions to Molecular Phys.*, p. 98):

> No coincidence between the vibrations of a radiating body and those of oxygen, hydrogen, or air could make any one of these substances a good absorber. They are physically incapacitated from communicating motion, and hence in an equal degree from accepting motion. The form of the atom [molecule?], therefore, or some other attribute than its period of oscillation [let us say, rather, some attribute on which that period depends], must enter into the question of absorption.

See also pages 102–105 (*loc. cit.*), where ozone is shown to absorb immensely more than oxygen. The atoms are here the same. It is the molecular form alone which has changed.

It is probable that some of the most important selective radiations of these elementary gases are of short wave-length and are not emitted until high temperatures are reached. We know that the linear absorption of cold oxygen in the visible spectrum is very feeble, requiring a long column of gas to show the A, B, and α groups of lines in the spectrum of a lime-light; but there is a region of great absorption in the extreme ultra-violet. Von Schumann finds that a layer of air 1mm. thick cuts off all rays beyond 0.175μ; and Liveing and Dewar (*Proc. R. Soc. London*, vol. 46, p. 222, 1889) have found that the absorption of 18 meters of oxygen in the ultra-violet is of the nature of a broad diffuse band, whose limits extend to greater wave-lengths on the less refrangible side as the pressure increases. At a pressure of 97 atmospheres, when the mass of oxygen in their tube was "rather greater than is contained in a vertical column of equal section of the Earth's atmosphere," the rays were completely absorbed to a wave-length of 0.2797μ. At 50 atmospheres the total absorption had its limit at 0.2696μ; and at 23 atmospheres the limit of extinction had receded to 0.2599μ.

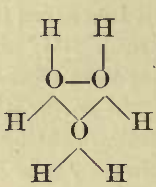
Two kinds of bands appear in the absorption-spectrum of oxygen, in regard to which

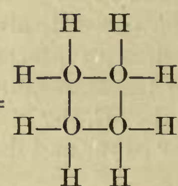
Professors Liveing and Dewar make some suggestions which are of interest in the present connection:

The absorptions of the class to which A and B belong must be those which are most easily assumed by the diatomic molecules (O_2) of ordinary oxygen. * * * As for the other class of absorption, the diffuse bands, since they appear to have intensities proportional to the square of the density of the gas, they must depend on a change produced by compression. This may either be the formation of more complex molecules, as for example O_4, corresponding to the deviation from Boyle's law exhibited by oxygen gas, or it may be the constraint to which the molecules are subject during their encounters with one another. Increase of temperature would affect the former, tending to diminish the number of complex molecules formed at a given pressure, but would have no effect on the latter, for though the number of encounters of the molecules in a length of time would be greater the higher the temperature, yet so long as the volume was unaltered the ratio of the duration of an encounter to that of free motion would be sensibly unaltered. So far as any change due to temperature has been observed, it is that a rise of temperature slightly weakens the diffuse absorptions (*loc. cit.* pp. 227, 228).

Consequently these observations favor the hypothesis that compression produces a limited number of complex and highly absorbent oxygen molecules which, even though few in number, are able to impress a peculiar character upon the spectrum.

Profs. W. Ramsay and J. Shields ("The molecular complexity of liquids," *Trans. Journ. Chem. Soc. London*, vol. 63, p. 1089, 1893), from their experiments on the surface tension of liquids as a function of the relative number of molecules per square centimeter of surface and the temperature, conclude that several molecules of water-vapor unite to form a complex molecule of liquid water; but ethyl oxide has the same molecule in the liquid as in the vaporous state. Regarding oxygen as tetravalent, the liquid molecules of water may be closed chains, *e. g.*:

$(H_2O)_3 =$ 

$(H_2O)_4 =$ 

At 60° C. the composition of the liquid molecule of water is $(H_2O)_3$, while at the temperature of maximum density most of the complex molecules are represented by the second formula.

The gradual formation of closed chains as the aqueous vapor approaches saturation,* must take place most readily if the molecules of vapor are not widely separated by diluting air. Meteorologists have often commented on the peculiarities of nearly saturated air, and some have conjectured that gaseous water exercises no appreciable absorption, and that the absorbent effects attributed to it are really due to a mist of liquid water, relative humidity being more important than vapor tension as an index of absorptive power. We have seen that gaseous water does produce a very potent influence of its own, but it seems to me to be demonstrated by what precedes that there is a remarkable increase in absorption by water at the critical point of incipient condensation, and as this point is somewhat closely approached. The suffocating sensations experienced in a very hot muggy atmosphere are attributable to the partial cessation of evaporation from skin and lungs, but the thermometric effects, such as the diminution of the daily range of temperature under a clear sky, which becomes very noticeable when the relative humidity is high, can be due only to strong absorption of the long-waved terrestrial radiations, and it is interesting to note that the difference between the absorption of liquid and vaporous water lies chiefly in the greater absorption of longer waves by the former. Professor Paschen says (*Wied. Ann.*, Bd. 51, S. 22, 1894):

Liquid water has a very deep absorption-band which reaches from [fluorite minimum deviation] 29° 55′ [3.58μ] to 30° 40′ [2.29μ], and has its maximum at 30° 23′, 2.92μ [subsequently corrected to 2.84μ], while the corresponding band of the water-vapor at 100° extends from 30° 18′ [3.00μ] to 30° 40′ [2.29μ], and has its maximum at 30° 31′, 2.66μ [subsequently corrected to 2.58μ]. That of the liquid water begins consequently at the same place as the gaseous on the side of the short waves, but ends at longer waves. A maximum also appears in [the absorption of] liquid water at 27° 40′ [6.02μ]; for water-vapor at 100° its position is 27° 53′ [5.85μ]. * * * If we remember that the emission-maximum of the oxyhydrogen flame lies at 30° 26′ [2.75μ], we can indeed say that

* Compare Regnault's observations cited, *ante*, p. 85.

liquid water absorbs the vibrations that the gaseous emits or absorbs. The liquid absorbs, however, in addition, such as belong to neighboring longer waves, and these indeed so much stronger that the absorption-maximum lies 3′ farther toward the long waves than the emission-maximum of the oxyhydrogen flame.

The spectral energy-curve of the oxyhydrogen flame, given by Paschen (*Wied. Ann.*, Bd. 51, Taf. 1, fig. 6, 1894), shows, in addition to the emission-band just mentioned, which corresponds with the absorption-band of the solar spectrum called X by Langley, also the correlatives of the solar bands Ω and Ψ. The band X is partly due, and the band Y wholly due, to the absorption-bands of carbon dioxide, discovered by Knut Ångström. I quote Paschen's description of his identifications:

Since Langley's bands Ψ, Ω, X, Y, etc., coincide within the errors of measurement with the absorption-bands determined by me, we may refer the given bands of the solar spectrum with great probability to the CO_2 and H_2O contained in our atmosphere. The wave-lengths of Langley's bands are: Ψ at 1.4μ, corresponding to the emission-band of H_2O at 1.4μ; Ω at 1.83μ, corresponding to an emission-band of H_2O at 1.83μ; $X = 2.64\mu$, corresponding to $H_2O = 2.66\mu$; Langley's band widens at low sun toward the longer waves. The new band arising at 2.94μ coincides with the absorption-maximum of liquid water which I find lying at 2.92μ. $Y = 4.6\mu$ corresponds to the CO_2 band at 4.63μ. From 5μ to 11μ Langley's solar spectrum is divided. Here lie the strong water-vapor absorptions (maxima at 7.1μ and 8.1μ). (*Loc. cit.*, p. 18.)

The last two wave-lengths were subsequently corrected after more accurate comparison of deviations from a fluorite prism and wave-lengths as given by a grating, becoming 5.86μ and 6.51μ. The limits of the great water band are also more nearly 5μ and 8μ, the correction affecting chiefly the wave-lengths above 5 microns. In this passage Dr. Paschen has misunderstood Langley's use of the word "maximum," which refers to an elevation in the energy-curve of the solar spectrum and not to the point of greatest absorption in a cold band. Langley (*Am. J. Sci.* (3), vol. 36, p. 403, 1888) distinctly says that 2.94μ is a subordinate maximum of the solar spectral energy-curve, and again he says (p. 404): "From 4.0μ to 4.5μ we have another region of almost complete absorption, followed by a maximum at 4.6μ." It appears probable that some of these numerical values will require further slight adjustment. Langley's original value for the center of Y, namely, 4.25μ, has since been confirmed by Paschen, who gives from his measures with a grating 4.245μ (*Wied. Ann.*, Bd. 52, S. 222).

The region of the solar spectrum from wave-length 2.3μ to 3.3μ is especially variable. Subordinate absorption-bands on the less refrangible side of X become apparently transposed in relative importance as the altitude of the sun above the horizon or the vapor-contents of the atmosphere change.

Observations made during the winter indicate that the band at 2.64μ is, with a high sun, largely filled up, especially on the less refrangible side. At noon a subordinate maximum has been found within the low sun limits of this band at 2.94μ, and a second one at 2.80μ frequently accompanies it, producing subordinate minima at 2.89μ and 3.02μ. As the absorption increases with a sinking sun, these subordinate maxima disappear to a very great extent, that at 2.80μ being the first to vanish, as well as the quickest to grow, so that at noon, on a cold day, it not only surpasses the maximum at 2.94μ, but even begins to approach that at 3.20μ, while, when the sun's altitude is less than 10°, the nearly uniform part of the band extends from 2.45μ to 3.15μ without a break. (Langley, *Memoirs of the National Academy of Science*, vol. 4, 2d Mem., p. 167, 1887.)

The varying form of the spectral energy-curve is doubtless due to the complex linear composition of the bands, individual lines, or groups of lines, having very different rates of growth as the absorbent depth varies; and to a corresponding variation in the emission of the several lines composing a group, coupled perhaps with the effect of self-absorption of its own radiations by the outer layers of a gas or vapor, is to be attributed the change in the measured positions of infra-red bands, noted by Langley and abundantly confirmed by Paschen. Of the two principal centers of the great absorption-band of water-vapor, the longer at 6.51μ appears to expand to still greater wave-lengths and the shorter at 5.86μ to still shorter wave-lengths, or in either case away from the common center, as the mass of the absorbent increases; and Paschen shows that the same movement occurs in the maximum points of the emission-bands of water-vapor as the temperature rises. The following table is quoted from his paper (*Wied. Ann.*, Bd. 52, S. 215, 1894), with wave lengths approximately corrected by his latest measures of fluorite dispersion (*Wied. Ann.*, Bd. 53, S. 822).

TABLE 67.—*Emission-spectrum of water-vapor.*

Temperature.	Position of the highest point in—			
	Maximum I.		Maximum II.	
	Deviation.	Wave-length.	Deviation.	Wave-length.
	° ′	μ	° ′	μ
Oxyhydrogen flame			28 29	5.28
Bunsen flame, 1,470°	26 58	6.60	28 25.5	5.34
1,000°	27 0	6.57	28 23	5.38
600°, approximately,	27 2.7	6.54	28 11	5.58
100°	27 5.5	6.50	27 51.3	5.87
17° (vapor)	27 6.5	6.48	27 48	5.92
17° (liquid)			27 40	6.02

The relative strength of the maxima of the strongest emission-bands in the spectral energy-curve of water-vapor at different temperatures follows closely the relation between the corresponding intensities at the same wave-lengths and temperatures in the spectrum of a black body; and the absolute intensities are not far behind. This indicates that at these points the radiant power of a comparatively small mass of vapor is nearly perfect; but this can not be said of the borders of the bands, and we need not expect that any completely consistent rule should be followed in their variation. The bolometer covers several alternations of radiant or absorbent spectral lines and their intervals, giving us the sum of the series. If the lines broaden and the intervals fill up until the lines coalesce completely, the limits of perfect radiation or absorption widen, and if the band is one-sided, its center changes its position in the spectrum. So long as there is no disintegration of atomic groupings increased heat may bring out new lines and give greater complexity to the spectrum, changing the aspect of a group. Since the centers of several aqueous bands shift to longer waves as the temperature rises, their structure probably resembles that of the A and B groups of oxygen, in beginning with strong lines on the side of the short waves and gradually fading out in a long series of feebler and more widely separated lines on the side of the long waves. The shifting of the center of Maximum II (Table 67) is in the opposite direction, and is also more rapid than that of I. In II the relatively greater increase of radiations of short wave length with rising temperature may assist, as suggested by Paschen, but only by aiding a process depending on structural detail of the band, which here fades out in the same direction as the shifting of the maximum ordinate in the spectral energy-curve of a black body. In I a similar greater increase of short than of long waves can not entirely overcome the structural shifting to the side of the long waves; and the same is true of the band X, while Ω and Ψ, situated in a part of the spectrum where the rate of increase of intensity with temperature varies rapidly with the wave-length at flame temperatures, have the structural shifting toward long waves slightly overbalanced by the more general formal change, as is shown in the next table, also taken from Paschen's work (*Wied. Ann.*, Bd. 52, S. 226), the wave-lengths corrected as before.

TABLE 68.—*Emission-spectrum of water-vapor.*

Temperature:	Band		Deviation ° ′	μ
Oxyhydrogen flame	X	Deviation	30 26.0	$\lambda=2.75$
Bunsen flame	X		30 25.5	2.77
Over 1,000°	X		30 26.0	2.75
500°	X		30 29	2.65
100°	X		30 30.8	2.59
Oxyhydrogen flame	Ω		30 52.0	1.78
Bunsen flame	Ω		30 51.5	1.81
Over 1,000°	Ω		30 51.0	1.84
Oxyhydrogen flame	Ψ		31 3	1.34
Bunsen flame	Ψ		31 2	1.38
Over 1,000°	Ψ		31 2	1.38

For the wave-lengths of the last three bands we need not depend on transformations from dispersion measures, since these maxima can be identified in the grating-spectrum of the Bunsen flame. Paschen's curve (*Wied. Ann.*, Bd. 50, Taf. IX, fig. 8) gives the following values:

(1) { Group Ψ extends from 1.33μ to 1.50μ.
Subordinate maxima, 1.35μ and 1.42μ; mean, 1.385μ.

(2) { Group Ω extends from 1.75μ to 2.10μ.
Subordinate maxima, 1.80μ, 1.86μ, and 1.97μ; mean, 1.877μ.

(3) { Group X extends from 2.42μ to 3.02μ.
Subordinate maxima, 2.51μ, 2.70μ, and 2.83μ; mean, 2.680μ.

In the absorption-bands of the solar spectrum, the deepest depression of Ω extends from 1.81μ to 1.87μ according to Langley ("Researches on solar heat," *Prof. Papers of the Sig. Serv.*, No. 15, p. 228, Washington, 1884), and the extension of the group on the side of the long waves is much feebler than in the emission-band of the Bunsen flame. The subordinate maximum of X at 2.83μ in the flame spectrum appears to agree with the minor band in the solar spectrum, called χ_1 by Langley, the wave-length of which was originally given as 2.89μ (*ante*, p. 101). That at 2.70μ agrees in position with one of the bands of CO_2.

Captain Abney and Lieutenant-Colonel Festing have photographed a continuous spectrum through several inches of water, getting the absorption-spectrum to a wave-length of 1μ ("Atmospheric absorption in the infra-red of the solar spectrum," *Proc. R. Soc. London*, vol. 35, p. 80, 1883). Three inches of liquid water give the following bands: (1) begins with a strong, sharp edge at 0.735μ and extends to 0.765μ, fading out thence on the side of the long waves, very gradually. Great A is included in its diffuse margin. (2) in like manner begins with a strong, sharp edge at 0.833μ, between Brewster's X and Y, and fades out gradully toward the long waves, the principal part of the band extending from 0.833μ to 0.875μ. The strong pair of lines, X, in the solar spectrum, due to calcium, wave-lengths 0.854μ and 0.866μ, is included in the diffuse margin. (3) is a very strong band between wave-lengths 0.942μ and 0.986μ, occupying nearly the same position as the bands in the solar spectrum, called $\rho\ \sigma\ \tau$ by Abney. It is bordered by hazy extensions and broadens to 0.88μ, when the depth of water is increased to 1 foot. These three bands are not composed of fine lines, but are diffuse, and they appear in photographs of the solar spectrum, superposed on groups of lines, and becoming very strong when the relative humidity approaches saturation. The authors say:

> Besides these linear absorptions, photographs taken on days of different atmospheric conditions show banded absorptions superposed over them. * * * On a fairly dry day the banded absorption is small, taking place principally between $\lambda 9420$ and $\lambda 9800$; a trace of absorption is also visible between $\lambda 8330$ and $\lambda 9420$. On a cold day, with a northeasterly wind blowing [this being for England the dry quarter], and also at a high altitude on a dry day, these absorptions nearly, if not quite, disappear. * * * When the air is nearly saturated with moisture, * * * except with very prolonged exposure, no trace of a spectrum below $\lambda 8330$ can be photographed. (*Loc. cit.*, pp. 80–81.)

Comparing these observations with those of Liveing and Dewar on the two kinds of oxygen bands, linear and diffuse, and with the facts adduced here which show that there is a very large increase in the absorptive power of aqueous vapor when nearly saturated, it seems probable that the diffuse bands of liquid water and of a saturated vapor are due to the complex aqueous molecules discovered by Ramsay and Shields, while the groups of fine lines in nearly the same positions in the spectrum belong to simpler molecules which no longer exist in the liquid state, but are present in variable proportion in the vapor, according to the temperature and the degree of saturation.

Abney and Festing in another paper ("The influence of water in the atmosphere on the solar spectrum," etc., *Proc. R. Soc. London*, vol. 35, p. 328, 1883) give spectral energy-curves for the crater of the positive carbon of an arc-light after absorption by various thicknesses of liquid water, obtaining evidence that nearly all of the great cold bands in the solar spectrum to 3μ are due to water. The liquid absorption-bands are, however, much more intense than the vaporous ones, and coalesce to form extensive regions of complete absorption. In addition to these curves, rough photographs of the solar spectrum to a wave-length of 2.2μ were taken on cold dry days, which confirm the presence of all of these water-bands and give their positions more accurately than the heat-measures made in the spectrum with a linear thermopile whose aperture was one-fiftieth of the length from the D-line to the end of the infra-red spectrum from a glass prism. In the

following table these thermal measures (*loc. cit.*, p. 332) are exhibited as percentage-transmissions in the last three columns:

TABLE 69.—*Transmission of spectrum by liquid water.*

	Radiation through empty glass cell.	Deflection through—			Transmission by—		
		$\frac{1}{8}$ inch water.	$1\frac{3}{8}$ inches water.	24 inches water.	$\frac{1}{8}$ inch water.	$1\frac{3}{8}$ inches water.	24 inches water.
					Per cent.	*Per cent.*	*Per cent.*
At *D*-line in yellow	7.5	7.3	6.8	3.2	97	91	43
Maximum in orange-yellow	8.7	8.7	8.5	4.0	100	98	46
Orange band	10.0	9.2	8.8	3.7	92	88	37
Maximum in red	16.7	16.7	16.0	10.7	100	96	64
Red band (near *A*)	19.3	18.5	17.0	2.3	96	88	12
Maximum near *Y*	22.8	22.8	20.6	1.4	100	90.	6
Band between *X* and *Y*	24.6	23.0	21.0	0.3	93	85	1
Maximum (Herschel's α)	25.4	24.7	22.0	0.0	97	87	
Band (Abney's $\rho\ \sigma\ \tau$)	27.7	21.5	5.3		78	19	
Maximum (Herschel's β)	30.0	26.3	10.0		88	33	
Band (Abney's Φ)	[26.7]	18.5	0.5		69	2	
Maximum (Herschel's γ)	[24.9]	19.0	7.0		76	28	
Band (Abney's Ψ)	18.5	0.7	0.0		4	0	
Maximum (Herschel's δ)	11.6	3.0			26		
Band (Langley's Ω)	[5.4]	0.0			0		
Maximum (Herschel's ε)	[2.9]	1.5			52		
Band (Langley's *X*)		0.0			0		

The extreme infra-red region of the spectrum, beyond the great water-band, has recently been explored by Prof. H. Rubens and E. Aschkinass (*Wied. Ann.*, Bd. 64, S. 584, 1898; translated in the *Astrophys. Journ.*, vol. 8, p. 176). The radiation from the mantle of a zirconium burner passing through a cast-iron tube 75 cm. long, "heated above 100° by four Bunsen burners beneath it," and fed with a permanent stream of aqueous vapor, was formed into a spectrum by a prism of sylvite, which at a wave-length of 18μ still transmitted "some 70 per cent., and at 20μ some 30 per cent., of the incident radiation." The general results are thus stated by the authors (*Astrophys. Journ.*, vol. 8, p. 190):

Water-vapor shows only faint absorption in the spectral region between $\lambda = 9\mu$ and $\lambda = 11\mu$, as compared with shorter and longer waved parts of the infra-red. From this follows the minimum [emission] observed in the emission [curve of hot water-vapor] at $\lambda = 10.7\mu$. Beyond 11μ the absorption begins to increase and becomes almost total at $\lambda = 20\mu$, whereby the maximum observed in the emission [from hot water-vapor] at $\lambda = 13.1\mu$ is explained. [The transferring of the maximum from 20μ in absorption to 13μ in emission is about what might be expected from the rate of increase of the radiation of a black body with shortening wave-lengths, combined with the larger transmission of the shorter waves by sylvite in this part of the spectrum.] In the region between 11μ and 18μ, water-vapor possesses six conspicuous maxima of absorption, which have according to our observations the wave-lengths $\lambda = 11.6\mu$, 12.4μ, 13.4μ, 14.3μ, 15.7μ, and 17.5μ.

The intensities of absorption of these six bands are 10, 20, 28, 43, 63, and 88 per cent., respectively; while at 20μ, as stated, the absorption is nearly 100 per cent. Beyond this point, at wave-lengths 24.4μ, aqueous vapor exerts only a very slight absorption (Rubens and Nichols, *Phys. Rev.*, vol. 4, p. 322, 1897; also *Wied. Ann.*, Bd. 60, S. 418, 1897). Since air was not excluded from the apparatus, it is possible that the total absorption at 20μ may have some other origin (see p. 113).

It will be evident that the interrelations of aqueous absorption and radiation in terrestrial meteorology must be complex. The radiations of clouds, the sea, and to a considerable extent those of moist earth and vegetation do not differ much from the radiant emission of a solid black body whose spectral energy-curve has its maximum, at terrestrial temperatures, in the immediate vicinity of the chief aqueous absorption-bands. The depletion of radiation is especially great if the coincidence of maximum radiation and principal absorption is exact; but the position of the maximum of aqueous absorption in the spectrum varies with the amount of water and with its physical state. The position of the maximum of the unabsorbed energy-curve also varies with the temperature of the radiating body and of the surface to which it radiates. Thus there is room for a great variety of combinations.

The apparent absorption of a layer of heated vapor is a differential one, being the resultant

of a series of operations made up of the sum of the original radiation of the body behind the vapor, minus the absorption exerted upon this radiation by the vapor, plus the emission of the vapor's own radiation, diminished by the absorption of the radiation from deeper vaporous layers by the vapor subsequently traversed. Since the vaporous emission varies with the temperature, the apparent absorption of the hot vapor likewise varies, except at temperatures too low for appreciable emission. This is very well shown in the series of absorption and emission curves for carbon dioxide at temperatures from 180° to 480°, given by Paschen (*Wied. Ann.*, Bd. 51, Taf. 1, fig. 8, 1894). At the highest temperature the apparent absorption is almost nothing, the radiant emission by the hot gas having counteracted its absorption. I have already noted (*ante*, p. 53) that this observation may be used in constructing a curve of temperature and depth at which absorption exactly compensates radiation. Another point on such a curve is given by the present measures (*ante*, p. 54), which show that for a temperature of 126° C. the effective radiating depth of carbon dioxide is only a little over 3 feet, let us say 100 cm. Paschen's measurement gives the temperature of 480° C., corresponding to a depth of 7 cm.

ABSORPTION OF RADIATION BY CARBON DIOXIDE.

Prof. Knut Ångström (*Wied. Ann.*, Bd. 39, S. 306, 1890; see also the preceding article, beginning p. 267), quoting observations by Lecher which show that the solar rays, after sifting by an air-mass of three atmospheres, are almost entirely deprived of those ether-waves which are susceptible of absorption by a moderate depth (1.05 meters) of carbon dioxide, concludes that, since the mean quantity of this gas in the atmosphere is less than 0.02 per cent., corresponding to a vertical depth of less than 1.5 meters of CO_2, and in three atmospheres to less than 4.5 meters, the transmission by one meter of carbon dioxide, within the limits of the CO_2 absorption-bands, is between 20 and 30 per cent., because the transmission of these particular rays, after a preliminary sifting through 0.5 meters of CO_2, has been found to follow the simple exponential law:

$$i = I \times t^m,$$

where I is the initial intensity of the limited radiation, t the transmission by unit-mass, m the actual mass of carbon dioxide (measured as the depth in meters of CO_2 traversed by the rays), and i the resultant intensity after absorption, by which law this degree of transmissibility secures the extinction of these rays. The strength of the chief carbon dioxide band in the solar spectrum also appears to agree with what might be anticipated from the known absorbent mass of this gas in the Earth's atmosphere, and the assumption that carbon dioxide gas has a simple molecule under every degree of dilution and that its absorption depends entirely upon the mass of gas traversed, is warranted.

One other assumption, however, is less commendable. While such small transmissions as 20 to 30 per cent. are the rule in limited regions, or bands, in the infra-red, it is not permissible to apply them, as Ångström has done, to the entire infra-red of the solar spectrum, thereby raising the estimated solar constant to four small calories.* It must be understood that the absorption of 20 to 30 per cent. is the mean absorption of a series of bands which include special rays totally absorbed, as well as intermediate ones which go free.

Ångström's result indicates that about 4.5 meters of carbon dioxide is sufficient to almost completely cut off the radiations absorbable by this gas, and taken in conjunction with Keeler's observation (*Am. J. Sci.* (3), vol. 28, p. 196, Sept., 1884) that 3.4 meters of carbon dioxide absorb 35.8 per cent. of the radiation from a Bunsen burner flame, the two ought to give approximately the relative values of CO_2 and H_2O radiations from this flame whose spectrum is purely one of bands. We should anticipate from these facts that not over 40 per cent. of Bunsen flame radiation is due to carbon dioxide, the rest coming mainly from water-vapor. This differs somewhat from the relative areas of the sums of the respective maxima in Paschen's curve of energy in the spectrum of the Bunsen flame, but as the composition of ordinary illuminating gas is variable,

*The application of the method by which Ångström obtains this value leads to the absurd result that over 60 per cent. of the original solar radiation is contained in the spectral region occupied by the bands of carbon dioxide. The limits of these bands have now been ascertained, and it is certain that they do not cover a length of the solar spectrum possessing more than a small fraction of this proportion of total radiant energy.

some range in the aqueous component of flame-radiation must be expected from this cause; and, besides this, the temperature of the flame is not a constant quantity, while the relative radiations of the different components do not vary with the temperature according to the same law. Nevertheless, I believe that the chief cause of the discrepancy is the considerable absorption by the fluorite of Paschen's prism of those emission-bands of aqueous vapor which are of greater wave-length than those carbon dioxide bands which furnish the larger part of the emission at high temperatures. Separating the CO_2 and H_2O bands in Paschen's curve (*Wied. Ann.*, Taf. IX, fig. 6), I found the relative areas were:

$$CO_2 : H_2O = 115 : 107$$

Making allowance for fluorite absorption increases the proportion of aqueous radiation, and reverses the ratio. Hence less than half the radiation of the hot gases of the Bunsen flame is due to carbon dioxide.

The growth of the band-emission, as temperature rises, agrees so nearly with the rate of increase of the total radiation of carbon dioxide that another reason is added to Paschen's argument in favor of the absolute discontinuity of its spectrum. Zöllner and Wüllner having reached the conclusion that a gaseous layer of infinitely great depth would send out a continuous spectrum from the broadening of the lines, a conclusion which presupposes that emission and absorption are never zero for any wave-length, Paschen tested the hypothesis by observing the absorption of 33 cm. of carbon dioxide at the maximum in the spectrum of an incandescent lamp ($\lambda = 1.4\mu$), a point quite outside the special regions of absorption for this gas. No difference greater than one part in four thousand could be found between the absorption of air and CO_2 at this point. "It is improbable that such absorptions, if they were present, should be the same; it is more likely that both are zero. However, in consequence of the moisture of the air, a small and equal absorption may have been present every time." (*Wied. Ann.*, Bd. 51, S. 33.)

"The fact that CO_2 exerts an absorption which at any other spectral positions than those of its absorption-bands is zero within the limits of errors of observation stands in connection with another fact that the breadth of the absorption-bands in question does not grow with increasing depth of the layer." The breadth of the principal CO_2 absorption-band, at $\lambda = 4.25\mu$, remained unchanged when the thickness of the cold gas-layer was increased from 0.3 cm. to 33.0 cm., the absorption of the maximum meanwhile increasing from 55 to 90 per cent. "For line spectra it follows * * * that with increasing thickness of the gas-layer in emission the lines only become brighter, but, in general, can not spread themselves over the entire spectrum." (*Loc. cit.*, p. 34). This does not prevent the greatest variety as to strength and rates of growth in such spectral lines as those of water-vapor, but the carbon dioxide spectrum is much simpler. Besides the two bands discovered by Knut Ångström

(1) at 2.3μ to 3.0μ, maximum 2.7μ, and

(2) at 3.9μ to 4.7μ, maximum 4.25μ,

Rubens and Aschkinass have discovered a third strong band in the extreme infra-red. With a thickness of a little more than 20 cm. of CO_2, "the whole region of absorption is limited to the interval from 12.5μ to 16μ, with the maximum at 14.7μ. Aside from this region not the slightest absorption could be detected between 8μ and 20μ, even when the box was completely filled with carbon dioxide," giving a depth of 65 cm. (*Astrophys. Journ.*, vol. 8, p. 191, 1898.)

The absorption at different points in band (3) (*loc. cit.*, p. 189, fig. 9) is as follows:

[Source, zirconium burner—Absorption by 20 cm. + of CO_2.]

Wave length.	Absorption.	Wave-length.	Absorption.	Wave-length.	Absorption.
μ	*Per cent.*	μ	*Per cent.*	μ	*Per cent.*
12.5	1	14.0	28	15.0	70
13.0	4	14.5	67	15.5	30
13.5	10	14.7	75	16.0	2

The absorption at the center of band (2), according to Paschen (*Wied. Ann.*, Bd. 51, S. 9), amounted to 30 per cent. from the small trace of carbon dioxide in the air of the room. This was

increased to 89 per cent. by the addition of a 7 cm. layer of the gas, but after this absorption was reached, further increase of the layer up to 33 cm. made little difference. At band (1) (*loc. cit.*, p. 10), an initial absorption of 10 to 20 per cent. by the air of the room was increased to about 30 per cent. by the 7 cm. layer, and to 43 per cent. by a layer of CO_2 33 cm. thick.

Owing to the very local distribution of the bands of carbon dioxide, the total amount of its absorption varies greatly with the temperature of the radiant source on whose emanations the absortion of the gas is exercised. Assuming that the absorption by a thickness of 1 inch of CO_2 at 30 inches pressure is identical with that of 48 inches of CO_2 at 0.625 inches pressure, we have from Tyndall's measures (*Contributions to Molec. Phys.*, pp. 37 and 170):

Temperature of source of radiation	100° C.;	1 inch of CO_2*	absorbs	2.2	per cent.
" " "	"	2 "	" "	3.4	"
" " "	270° C.;	1 "	" "	6.3	"
" " "	"	2 "	" "	7.6	"

Hence the absorption of radiation from the source at higher temperature is two to three times as great as for the radiation from the low-temperature source. The reason for this is seen on comparing the spectral energy-curves of the sources. The chief band of carbon dioxide ($\lambda = 4.25\mu$) falls near the maximum ordinate in the curve for 270°, but affects a relatively insignificant region of the spectrum of a body at 100° C. On the other hand, the chief absorption by water-vapor agrees more nearly in wave-length with the maximum of the source of lower temperature, whose radiation, in consequence, is relatively more depleted in passing through moist air than that of a hotter body.

From the figures just given we may infer that the amount of carbon dioxide in 100 meters of air at normal pressure absorbs about 2.5 per cent. of the radiation from a source at 100° C.

APPLICATION OF THE FOREGOING STUDY OF GASEOUS ABSORPTION TO THE RESULTS OF LABORATORY EXPERIMENTS.

We are now ready to correct the measured values of apparent gaseous radiation, obtained in Method C, by allowance for the modifications introduced by gaseous absorption.

By Table 48, p. 71, the apparent radiation of 141.8 cm. of carbon dioxide was:

At excess 50° C.	$r = 93 \times (10)^{-9}$ radim
" " 80° C.	260 " "
" " 100° C.	482 " "

According to the data in the chapter on screens, the corresponding measured radiations of a screen of sooted copper (the initial temperature being 35° C.) were:

At excess 50° C. (358° absol. T.)	$r = 1335 \times (10)^{-9}$ radim
" " 80° C. (388° absol. T.)	2321 " "
" " 100° C. (408° absol. T.)	3095 " "

From the curve (fig. 18), representing the absorption by carbon dioxide of radiation from sooted copper at 100° C., founded on the observations of Tyndall, already cited, it may be inferred that a 5-foot layer of CO_2 intercepts 18.4 per cent. of the rays. The corresponding absorptions for the sources at lower temperatures will be about 0.8 and 1.5 per cent. smaller, or 17.6 and 16.9 per cent., respectively. Hence the disk-radiation, in the extreme positions, was diminished as follows:

Depth.	Temperature-excess.	Disk-radiation absorbed by CO_2	and by rock-salt.
60 in.	50° C.	$1335 \times 10^{-9} \times 0.169 = 225.6 \times 10^{-9}$	169×10^{-9}
60 in.	80° C.	$2321 \times 10^{-9} \times 0.176 = 408.5 \times 10^{-9}$	306×10^{-9}
60 in.	100° C.	$3095 \times 10^{-9} \times 0.184 = 569.5 \times 10^{-9}$	427×10^{-9}

* Compare *ante*, footnote on p. 87.

At the smallest distance ($4\frac{1}{4}$ inches) the disk-radiation must have been diminished thus:

Depth.	Temperature-excess.	Disk-radiation absorbed by CO_2	and by rock-salt.
$4\frac{1}{4}$ in.	50° C.	$1335 \times 10^{-9} \times 0.055 = 73.4 \times 10^{-9}$	55×10^{-9}
$4\frac{1}{4}$ in.	80° C.	$2321 \times 10^{-9} \times 0.055 = 127.7 \times 10^{-9}$	96×10^{-9}
$4\frac{1}{4}$ in.	100° C.	$3095 \times 10^{-9} \times 0.055 = 170.2 \times 10^{-9}$	128×19^{-9}

All of these radiations have suffered an absorption of about 25 per cent. by the rock-salt plate,* as given in the last columns for comparison with the measured radiations also absorbed to

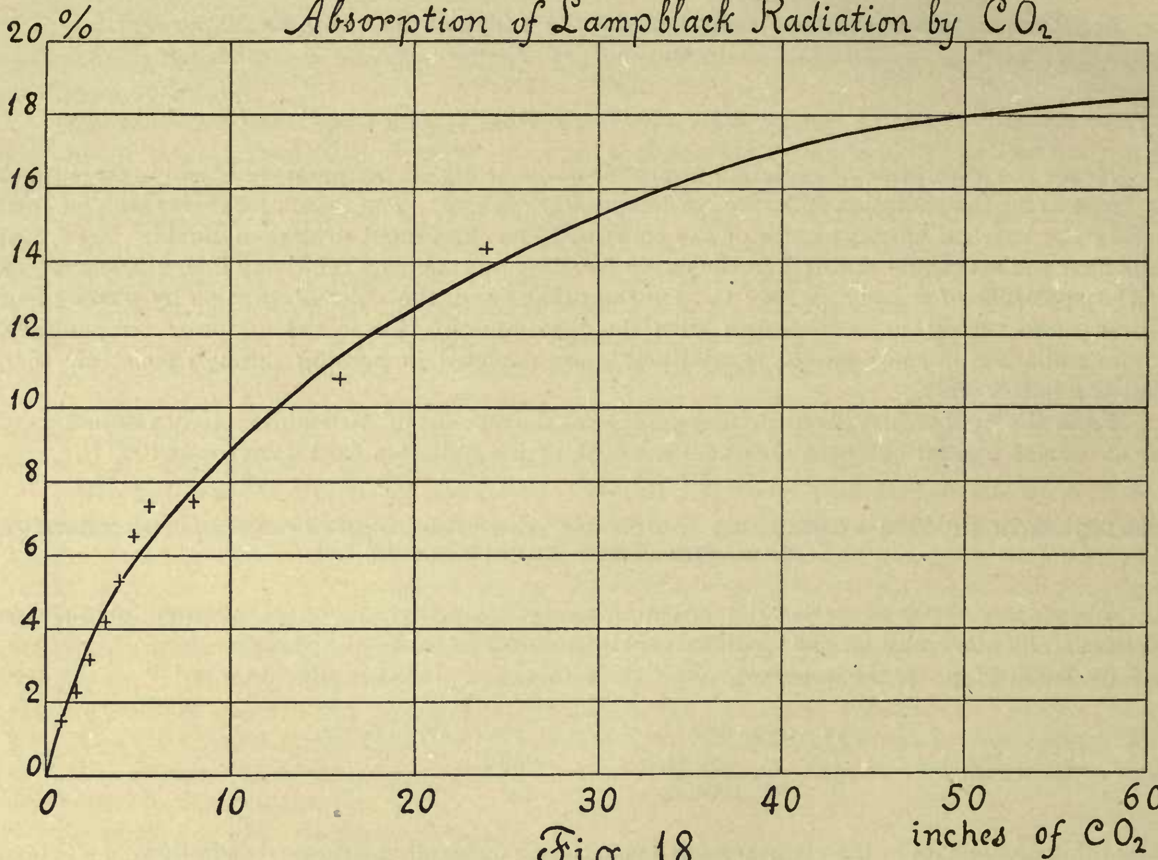


Fig. 18

approximately the same extent. The observed apparent radiations of the gas must be increased by the differences of these numbers and further increased by the absorption of rock-salt.

Temperature-excess.	Radiation of CO_2 through rock-salt, affected by CO_2 absorption but corrected for salt.
50° C.	$\{93 + (169 - 55)\} \times (10)^{-9} \div 0.75 = 207 \times 10^{-9} \div .75 = 276 \times 10^{-9}$
80° C.	$\{260 + (306 - 96)\} \times (10)^{-9} \div 0.75 = 470 \times 10^{-9} \div .75 = 627 \times 10^{-9}$
100° C.	$\{482 + (427 - 128)\} \times (10)^{-9} \div 0.75 = 781 \times 10^{-9} \div .75 = 1041 \times 10^{-9}$

Finally these values must be further corrected for absorption by $4\frac{1}{4}$ inches of carbon dioxide.

Only approximate estimates are available for this quantity. From Tyndall's *Contributions*, page 185, Table XXXV, two minimum values of the absorption may be obtained A layer of CO_2 34 inches deep absorbed $\frac{2.45}{3.7} = 0.662$, and one 13.1 inches deep absorbed $\frac{10.2}{16.8} = 0.607$ of the radiation from a more distant layer of the same gas. A smooth curve through these points and the

* See my determination of this quantity. *Astrophys. Journ.*, vol. 8, p. 211, Nov., 1898.

zero point, as in fig. 19, gives an absorption of 40 per cent. for a depth of 4¼ inches. Since a portion of the radiation came from the walls of a metal tube and was more transmissible than the gaseous radiation, and since the gaseous radiation does not increase much after the third foot, the true absorption of its own rays by CO_2 is certainly greater than that given, but I am unable to fix

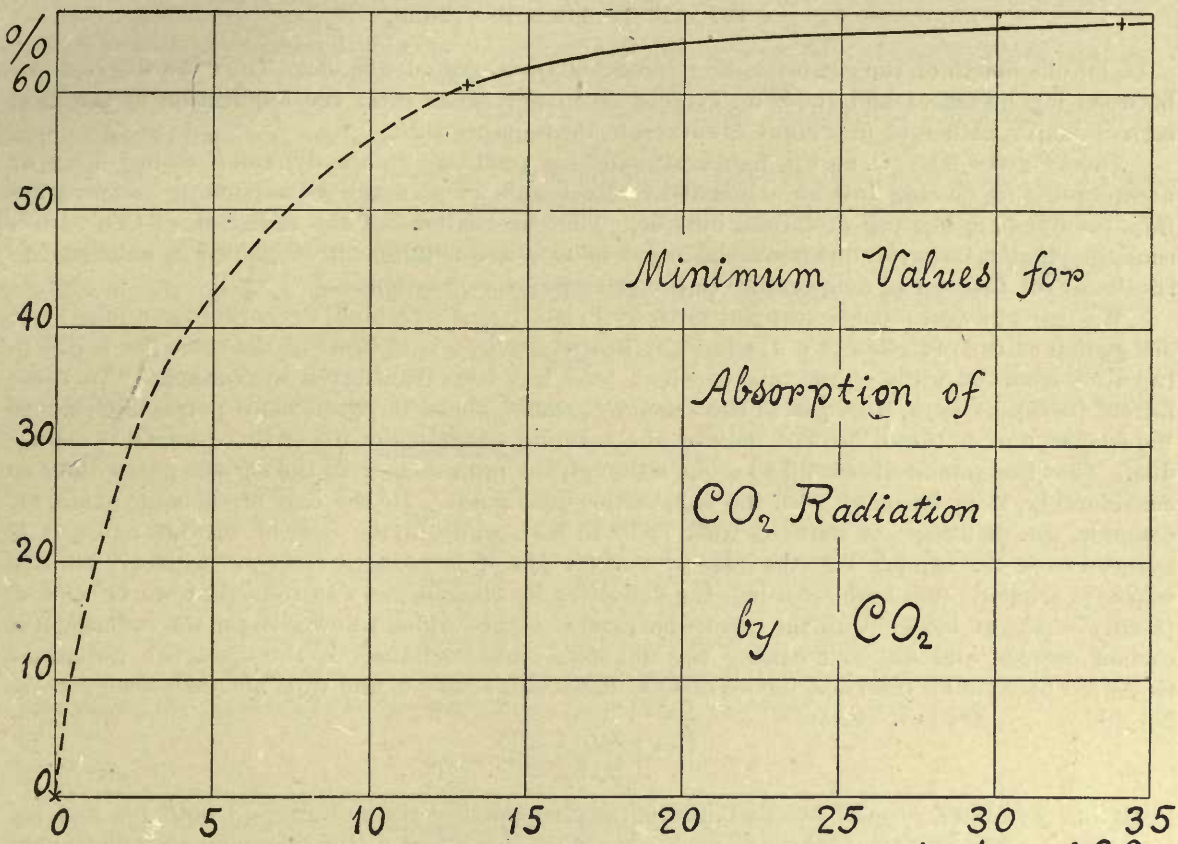


Fig. 19

a more definite value for the absorption by the smallest depth. Accordingly, the true radiations which the bolometer might have recorded, if it could have received the unobstructed emission of rays from a free layer of carbon dioxide 141.8 cm. deep, are:

$$(50°)\quad 276 \times 10^{-9} \div .6 = 460 \times 10^{-9} \text{ radim.}$$
$$(80°)\quad 627 \times 10^{-9} \div .6 = 1045 \times 10^{-9} \text{ radim.}$$
$$(100°)\quad 1041 \times 10^{-9} \div .6 = 1735 \times 10^{-9} \text{ radim.}$$

Absorption by dry air being, according to Tyndall, one-ninetieth that of carbon dioxide, the corresponding disk-corrections for air are, respectively, 1, 2, and 3×10^{-9}, and with further allowance for absorption by rock-salt the corrected air radiations are:

$$(50°)\quad (139 + 1) \times 10^{-9} \div 0.75 = 187 \times 10^{-9} \text{ radim.}$$
$$(80°)\quad (390 + 2) \times 10^{-9} \div 0.75 = 523 \times 10^{-9} \text{ radim.}$$
$$(100°)\quad (723 + 3) \times 10^{-9} \div 0.75 = 968 \times 10^{-9} \text{ radim.}$$

The radiation of carbon dioxide is thus found to exceed that of air in every case. The absorption of rock-salt for air radiation may differ from the absorption found for ordinary low-temperature sources of radiation, but not greatly, as the close agreement of results obtained by Method B without absorbent plates proves. (*Ante*, p. 71.)

Tyndall's comparisons of radiations from gases dynamically heated (quoted *ante*, p. 76) were made with 3-foot layers. As I have already explained, the radiation of carbon dioxide is almost exactly the same for a 3-foot layer as for one of 5 feet; but the air radiation with the shorter depth is reduced proportionally. Hence at 50° excess the radiation of 3 feet of air should be

$$\frac{3}{5} \times 188 \times 10^{-9} = 112 \times 10^{-9} \text{ radim},$$

or about one-fourth of the corresponding radiation from carbon dioxide. Thus the discrepancy between my measures and those of Tyndall no longer exists after the application of the final corrections, or, rather, at first sight, is turned to the opposite side.

Theory gives 30.5° C. as the temperature-excess produced by the dynamic heating of air at normal pressure flowing into an exhausted receiver, and 23° C. is the corresponding temperature from the dynamic heating of carbon dioxide. The observations of the radiation of CO_2 with a cooling cylinder, however, do not extend as low as this, and nothing will be gained by substituting results at the theoretical temperature in the preceding computation.

We may now test a conjecture put forth by Tyndall, that a residual deflection remaining after absorption of the radiation of a dynamically heated gas by a cold layer of the same gas is due to radiation from the walls of the tube to which heat has been transferred by contact. "To these latter" [rays], he says, "the gas in the second chamber would be much more permeable than to the former, and to these latter, I believe, the residual deflection of 6°, or thereabouts, is mainly due. That this number turns up so often, although the radiations from the various gases differ so considerably, is in harmony with the supposition just made. In the case of carbonic oxide, for example, the deflection is reduced from 13.7° to 6.3°, while in the case of nitrous oxide it is reduced from 19.5° to 6.2°; in the case of olefiant gas it is reduced from 59° to 10.4°, while in other experiments (not here recorded) the deflection by olefiant gas was reduced from 44° to 6°." (*Contributions*, p. 186.) With the quadruple ratio (4.11 : 1), which I now give for the radiations of carbon dioxide and air, and calling the unknown tube radiation x, the apparent radiations measured by Tyndall from 36.3 inches of CO_2 (deflection = 16.8°), and from air (deflection = 8° to 9°) give

$$x = \frac{(4.11 \times 8.5) - 16.8}{3.11} = 5.8$$

justifying Tyndall's supposition, and incidentally supporting the accuracy of both his and my measures. After wandering through such a maze of corrections as the foregoing an independent check does not come amiss.

The true radiations from the dynamically heated gases in Tyndall's work were

$$CO_2,\ 11.0°;\ \text{air},\ 2.7°;$$

but the large deflections, obtained when blackened tubes were used, were probably due, as I have suggested (*ante*, p. 76–77), to heat developed by condensation of gases in the pores of lampblack.

The experiment on the radiation of steam (*ante*, p. 72) may now be reduced. The density of steam at 135° C. (excess 97°), and at normal pressure, being $\frac{1}{583}$, the liquid equivalent of 142 cm., at 126 mm. pressure, is

$$142 \times \frac{1}{583} \times \frac{126}{760} = 0.040\ 381 \text{ cm.},$$

which by fig. 13 (*ante*, p. 91) will absorb 5.1 per cent. of radiation from lampblack at 100°. The disk having an excess of 97°, the correction for absorption of disk-radiation by vapor and salt may be taken as

$$2942 \times 10^{-9} \times 0.051 \times 0.75 = 113 \times 10^{-9} \text{ radim},$$

and the apparent radiation of steam, reduced with the instrumental constant at the epoch, is

$$38 \times 43.8 \times 10^{-9} = 1664 \times 10^{-9} \text{ radim}.$$

The absorbent layer contained 0.000 224 cm. of equivalent liquid water whose absorption exercised on the special aqueous rays is by no means negligible, as shown by Tyndall's observations on the

aqueous absorption of rays from the hydrogen flame (cited *ante*, p. 88), from which an absorption of about 1.9 per cent. may be inferred in the present case, and the measurement of radiation from a 5-foot layer of low-pressure steam, as finally corrected, is:

$$\frac{\{113 + 1664 + (0.019 \times 1664)\} \times 10^{-9}}{0.75} = 2412 \times 10^{-9} \text{ radim.}$$

Reduced to radiant emission to a complete hemisphere, this becomes 0.01247 radim, which is about 81 per cent. of the constant for lampblack at the given temperature.

Before stating the total gaseous radiation a more accurate reduction of the observations at different depths than was possible before shall be given.

From the curve (fig. 18) the values of CO_2 absorption of disk-radiation, corresponding to even feet, are taken and used to correct the percentages in Table 40. By page 108, the correction to CO_2 radiation for absorption of disk-radiation (both being absorbed by rock-salt) is $\frac{299}{482} = 62$ per cent. This will appear in the final column of the next table, the other numbers in this column being derived from it.

TABLE 70.

Depth of CO_2	CO_2 absorption of disk-radiation.	$a - a_1$	$b = \frac{a - a_1}{12.9}$	Correction $c = b \times 62$ per cent.
Inches.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
4½	a_1= 5.5	0	0	0
12	a_2= 9.6	4.1	31.8	+19.7
24	a_3=13.9	8.4	65.1	+40.4
36	a_4=16.4	10.9	84.5	+52.4
48	a_5=17.8	12.3	95.3	+59.1
60	a_6=18.4	12.9	100.0	+62.0

Applying the corrections in the last column to the observed radiations we have:

TABLE 71.

Depth.	0.35 foot.	1 foot.	2 feet.	3 feet.	4 feet.	5 feet.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
CO_2 radiation	0	33.3	72.0	98.7	100.0	97.1
Correction (c)	....	+19.7	+40.4	+52.4	+59.1	+62.0
Sum		53.0	112.4	151.1	159.1	159.1
Corrected CO_2 radiation expressed as a percentage of the highest value.	0	33.3	70.6	95.0	100.0	100.0

The air values in Table 40 will not be changed appreciably by a correction for the absorption of disk-radiation by air. Accordingly, the percentage of radiation from different depths of the two gases may now be finally stated.

TABLE 72.

	CO_2	Air.		CO_2	Air.
Feet.			*Centimeters.*		
5	100	100	125	100	125
4	100	80	100	100	100
3	99	60	75	91.5	75
2	80	40	50	70.5	50
1	48	20	25	40.5	25
			2.5	6	2.5

Values obtained with the factor E_2 (p. 23), and representing the actual radiation falling upon the bolometer as measured in absolute units, are reduced to hemispherical emission by multiplying by the factor:

$$\frac{2\pi \times (28.7)^2}{0.19 \times 5.2685} = 5170$$

An approximate conception of the relations between the total radiation passing through the unit of surface in the unit of time, the temperature, and the depth from which radiation proceeds, may be obtained for carbon dioxide and air by combining the variations from change of temperature with those for change of depth, which is done in the following table (73) completing the experimental part of this research.

TABLE 73.

Depth.	125 cm.		100 cm.		75 cm.		50 cm.		25 cm.		2.5 cm.	
	Air.	CO_2.	Air.	CO_2.	Air.	CO_2.	Air.	CO_2.	Air.	CO_2.	Air.	CO_2.
°												
100	.00442	.00897	.00353	.00897	.00265	.00821	.00176	.00632	.00088	.003[illegible]3	.00009	.00054
90	.00325	.00697	.00260	.00697	.00195	.00638	.00130	.00491	.00065	.00282	.00007	.00042
80	.00238	.00540	.00190	.00540	.00143	.00494	.00095	.00381	.00048	.00219	.00005	.00032
70	.00173	.00417	.00138	.00417	.00104	.00382	.00069	.00294	.00035	.00169	.00004	.00025
60	.00123	.00319	.00099	.00319	.00074	.00292	.00049	.00225	.00025	.00129	.00002	.00019
50	.00086	.00238	.00068	.00238	.00051	.00218	.00034	.00168	.00017	.00096	.00002	.00014
40	.00056	.00169	.00045	.00169	.00034	.00155	.00023	.00119	.00011	.00068	.00001	.00010
30	.00035	.00111	.00028	.00111	.00021	.00102	.00014	.00078	.00007	.00045	.00001	.00007
20	.00019	.00064	.00016	.00064	.00012	.00059	.00008	.00045	.00004	.00026	.00000	.00004
10	.00008	.00027	.00006	.00027	.00005	.00025	.00003	.00019	.00002	.00011	.00000	.00002

These values in fractions of a radim are plotted in Fig. 20.

At 100° C. excess of temperature, and at a somewhat greater excess above the freezing point, air 1 cm. deep radiates 0.000 036 radim, or 0.000 000 36 radim per degree. With an excess of only 1° C. the radiation may be estimated as about 0.000 000 06 radim. These quantities are considerably smaller than the 0.000 001 14 radim found by Professor Hutchins (*Am. J. Sci.* (3) vol. 43, p. 362, 1892), who, however, did not dry his air. Moreover, as has been shown, Professor, Hutchins underestimated the depth of the radiant layer of gas, which makes his measurement of radiation per unit of depth too large. On the other hand, my values exceed that deduced by Maurer from meteorological considerations, namely, 0.000 000 011 6 radim. The difference here is very likely due to absorption by air of its own radiation, where large masses are involved, as in the atmosphere.

The region of the spectrum in which the radiation of air lies, may possibly be inferred from the following facts: A region of powerful oxygen absorption exists in the ultraviolet, to which, in all probability, a strong band of emission corresponds; but it is not likely that any emission, produced by simple heating, can be felt in this part of the spectrum at low temperatures. The linear oxygen absorption groups—A, B, and a—in the red, and a series of faint diffuse bands, of which the strongest corresponds with Brewster's telluric band δ ($\lambda = 0.565\mu$ to 0.585μ) in the yellow, together with any others of a like order which await identification in the infra-red, are too insignificant to have emission counterparts which will account for any appreciable fraction of the low-temperature radiation of this gas. Nitrogen and argon are, so far as we now know, of still less importance, since no telluric bands have as yet been traced to their presence in the atmosphere.

Two facts remain to be considered. Hutchins found that a plate of quartz, 0.5 cm. thick, reduced the deflection from hot air from 151 div. to zero; and it has been noted (*ante* p. 34) that 0.315 cm. of glass appeared to transmit 8 per cent. of air-radiation. Besides the region of quartz-absorption at 0.103μ, H. Rubens and E. F. Nichols (*Phys. Rev.*, vol. 5, p. 105, Aug., 1897) have found bands of metallic reflection and total absorption for this substance at 8.50μ, 9.02μ, and 20.75μ. The first two of these bands, with the neighboring region from 8μ to 9.5μ through which transmission by a layer of quartz, so thin as 18μ, does not exceed 10 per cent. (Nichols, *Phys. Rev.*, vol. 4, p. 307, 1897), can not cover the atmospheric bands which we are seeking, since in this part of

the spectrum solar rays pass through the atmosphere easily, and the principal emission of radiation from hot aqueous vapor, between 5μ and 8μ, also lies outside of this region. Hence it is perhaps permissible to infer that the low-temperature emission of air, which is so completely absorbed by quartz, has a wave-length not far from 20.75μ, and that air also absorbs strongly in this region; but, if so, the ratio of air-radiation to the radiation of carbon dioxide ought to diminish as the temperature rises, at least until those very high temperatures are attained which favor the emission of the ultra-violet band of oxygen, and there is no evidence of this. I am not disposed

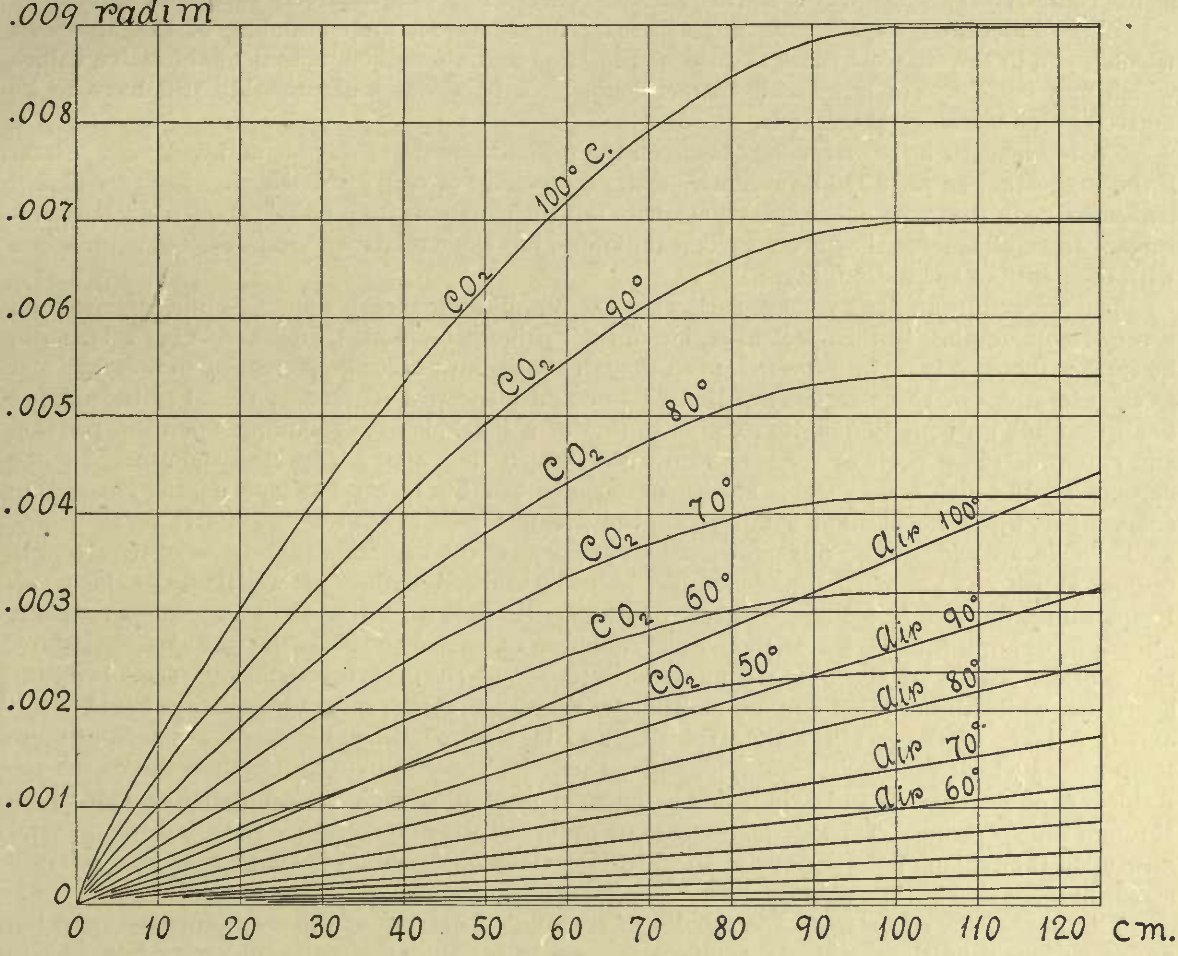


Fig. 20

Variation of Gaseous Radiation With Depth and Temperature.

to insist upon my observation of a feeble transmission of radiation from air by glass, because it rests upon a very small deflection, but, if genuine, it indicates a discontinuity and essential difference in the absorptions by glass and quartz at this extreme wave-length.

GENERAL APPLICATION OF THE PRECEDING STUDIES OF ABSORPTION AND RADIATION TO THE PROBLEMS OF ATMOSPHERIC RADIATION.

We have seen that a highly absorbent gas, and one which is also an equally powerful radiant in thin layers, may have little more radiative power than a bad radiator when the depths are greater, the positions of the two being finally reversed at still greater depths, as indicated by the extended curves of fig. 20, and that, in fact, there is not as much difference as might be imagined

between the radiation of the different constituents of the atmosphere at ordinary temperatures and when in large masses. The facility with which a highly radiative vapor parts with its heat is largely annulled by self-absorption of its own radiations in deep layers, and since in gases heat is transferred from molecule to molecule with the greatest ease, it is probably a fact that small masses of mixed gases or vapors, such as are used in laboratory experiments, radiate chiefly by their most highly radiative molecules, the others transferring their heat to these kinetically;* but in such great masses as are concerned in atmospheric thermal and radiant processes, it is the feebly radiative molecules which act as radiators, except in a comparatively thin outer layer.

While laboratory experiments are necessary for a correct understanding of the processes which go on in the simplest cases of gaseous radiation and absorption, actual quantitative values which may be of use in large-scale meteorological computations will probably still have to be derived by meteorological methods.

There seems to be some analogy between the radiant powers of dry air and rock-salt. Both, if the suggestion on page 113 be accepted, emit ether-waves ot very great length. Both are highly transmissive in that part of the spectrum where fall the emissions from bodies at ordinary temperatures. In small masses they are very bad radiators, but their relative radiant efficiency increases with the depth of the radiant layer.

The powerfully radiant vapors, such as ammonia, like the metals among solids, radiate from a very feeble depth. In the spectral region of their principal emission, after exceeding this depth, no further increase is to be expected, even though the radiant layer be increased to infinity; and as the radiations of these vapors are limited to definite spectral regions, the total emission must finally exhibit an equally definite relation to that of a black body, depending upon the position and extent of those parts of the spectrum within which the vapor is a perfect radiator. In like manner, a gas which is very feebly absorbent or radiant in thin layers, has some depth of maximum efficiency at which its peculiar bands attain the greatest possible development. If these bands, while feeble, are wider, or occupy more extensive regions of the spectrum than those of the strongly radiant vapor, and are of such wave-lengths as to be emitted with equal readiness at the given temperature, the gas in a layer of great depth may surpass a like depth of vapor as a radiator, although, when in thin layers, the vaporous radiation immensely exceeds the gaseous. Again, if the emission bands of the gas are more numerous, and occupy very extensive regions of the spectrum, while those which can be emitted by the vapor at the same temperature are of small extent, a layer of the gas less than the depth of maximum efficiency (except, perhaps, at some temperature which especially favors the vapor's emission) may radiate better than the vapor, the feebleness of the gaseous emission-bands being compensated by their great number or wide range through the spectrum. The rate of increase of radiation with temperature-elevation will depend also upon the region of the spectrum to which the emission is confined, long waves increasing in strength more slowly than short waves.

The discrepancies between the results of different observers of gaseous radiation, working under various conditions of depth, temperature, etc., after the elimination of errors involved in methods of observation, are capable of being reconciled, and seem to demand varieties of spectral structure, such as those which have been mentioned, for their explanation. To apply the argument to the components of the atmosphere: Carbon dioxide, so far as is now known, has only three emission-bands in the infra-red. Within narrow spectral limits, the radiation of this gas is very powerful, requiring only about a meter-layer to give maximum efficiency. The almost equally slow increase of air-radiation with rise of temperature is perhaps due to the long wave-lengths of its bands; but the very gradual growth of its radiation as the depth enlarges is best explained by the supposition of an extensive spectral region filled with numerous feeble emission-bands which grow in strength very slowly as the depth increases, but which, nevertheless, in their sum total, eventually surpass the radiation of the few strong bands of carbon dioxide. Whether oxygen, nitrogen, or argon are concerned in this primarily feeble emission can not be stated. In a different category from either of the other atmospheric constituents, is water-vapor. Its spectrum consists of many bands composed of very numerous fine lines. Some of these bands are strong, reaching maximum development with a slight depth, while others grow slowly. The extent of spectrum

* See Tyndall's experiments in "varnishing" air molecules with those of more powerfully radiant vapors.

filled with these groups is very great, and thus the radiation is large with a small thickness of vapor, and yet continues to increase through a wide range of depths. The importance of aqueous vapor as a radiator is therefore great; nevertheless, in layers of atmospheric dimensions, there may not be as much difference in the relative efficiency of atmospheric constituents as might at first appear. Throughout the greater part of this vast aerial envelope the gaseous molecules can not radiate, except so far as the stronger radiators emit to the weaker, and these to the outer world. The different sorts are quite independent of each other, but those of a kind are hemmed in by other molecules of the same absorbent properties which cry "no thoroughfare" to ether-waves which have their own vibratory period. Thus it is that, in the upper air, temperature remains almost constant through day and night, and only changes as the vertical circulation of storms, and the general movement of the entire atmosphere from equator to poles and back, replaces the air at any given level and terrestrial position by other air which has acquired its temperature elsewhere under freer conditions. Only at the borders of its domain is any constituent of the air entirely free to change its temperature by its own radiation.

An important relation results from the facts embodied in the theory of a maximum radiant depth in a gas, when combined with the further knowledge that this depth is reached at different distances for particular wave-lengths, and is quickly attained for those rays which lie near the maximum of an emission-band. It seems permissible to say already that so far as gaseous radiation depends upon simple heating of the gas, the ordinates of the maxima in bands of different wave-length (the depth being sufficient to give maximum radiant efficiency for these special rays) are related to each other in the same way as are the ordinates in the spectral energy-curve of a black solid body. As the temperature rises, the heights of the emission-bands of short wave-length increase more rapidly than those corresponding to the longer waves, and with the limitation noted as to manner of excitation, bands at the shortest wave-lengths only become sensible at those high temperatures at which similar radiations first appear in the spectrum of a black solid. Not only is this relative agreement maintained, but the absolute energies in the spectrum at a gaseous band-center and at the same point in the spectrum of lampblack for the same temperature are almost identical, any slight inferiority of the gaseous radiation being probably attributable to the linear constitution of the band and the absence of the condition of maximum efficient depth for some of the rays of the complex bundle. This point has been established for aqueous vapor and carbon dioxide by the observations of Paschen on the emission of heated gases. After noticing facts brought forward by Pringsheim, among others that thin wires are only heated to about 150° C. by certain flames, such as that of carbon bisulphide, "which, notwithstanding, send out an abundant and absolutely blue light," and commenting that, in spite of the low temperature of the wires, "the luminous molecules may, nevertheless, have a very high temperature"—a conclusion which has also been reached by Smithells on theoretical grounds—Paschen demonstrates experimentally that, whatever part chemical action may have in originating high temperatures, the vapor of water and carbon dioxide whose discontinuous emissions make up the chief part of the spectrum from a Bunsen-burner flame, radiate solely by virtue of their heat, however imparted. The emission-bands discovered by Julius in flame-spectra were reproduced by Paschen by simply heating the gases without any combustion whatever. The emission-bands of carbon dioxide were "still certainly perceptible" with the gas at 73° C., at which temperature there can be no question of dissociation or of chemical action; and the emission from aqueous vapor was followed to 280° C. The maximum of CO_2 radiation at wave-length 4.3μ, exhibited the following intensities at the given temperatures: At 842° C., 566 div.; at 707° C., 357 div.; at 450° C., 114 div.; at 306° C., 37 div.; at 204.5° C., 11.1 div.; at 165° C., 6.6 div.; at 114° C., 3.0 div.; and the highest maximum of water-vapor at wave-length 2.7μ gave: At 900° C., 146 div.; at 638° C., 25.4 div.; at 496° C., 5.6 div.; at 400° C., 2.1 div.; at 284° C., 0.6 div. (*Wied. Ann.*, Bd. 50, S. 428, 429, 1893.)

Here radiation has increased with temperature at a more rapid rate for water than for carbon dioxide, or in accordance with the usual law for continuous spectra where the shorter waves have a more rapid rate of increase of energy than the longer; but the relation between the intensities of maxima in different parts of the spectrum is not given by these experiments, since the maxima compared do not belong to the same substance, nor can it be a definite one even for a single radiator unless the depths exceed maximum efficiency for every one of the bands.

In the spectrum of steam, 7 cm. deep, at 500° C., the heights of the long-waved maxima are nearly equal to the corresponding ordinates in the spectral energy-curve of lampblack at the same temperature. At wave-length 5.6μ, "where the water-vapor spectrum has the intensity 87 mm., lampblack at 500°, under like conditions, gives a galvanometer deflection of about 110 mm." At 6.5μ "these intensities are for water 66, for lampblack about 80," but at 2.7μ "on the other hand, for water 139, for lampblack 320 mm.," showing that the depth of 7 cm. is insufficient to fully develop the radiation of the last-named band. (*Wied. Ann.*, Bd. 51, S. 36, 1894.) The height of the emission-maximum at 2.7μ was increased from 20 mm. to 139 mm. when the depth was increased from 3 mm. to 70 mm. (*Loc. cit.*, p. 35.)

The changes in the spectral energy-curve of radiant aqueous vapor produced by variations of temperature are still more marked than those from varying depth. Thus while the aqueous absorption is most intense in the long-waved bands, and while these bands are also most prominent in the emission at low temperatures, the band at 2.7μ has a height twenty times as great as the former in the spectrum of the oxyhydrogen flame. Hence different bands in the spectrum of the same substance follow different laws of increment, both as to temperature and as to depth.

Carbon dioxide at wave-length 4.3μ, in even so small a depth as 7 cm., behaves very much like a black body, both as regards the absolute intensity of its radiation and its variation with the temperature. Paschen's curve for the latter quantity (*Wied. Ann.*, Bd. 51, Taf. 1, fig. 9) falls but little below the corresponding curve for lampblack, indicating that 7 cm. is very near the maximum efficient depth for certain rays from this gas.

It is not to be expected that a vapor which is quite colorless and transparent for luminous rays should give a continuous visible spectrum even when highly heated; but the same gas in another part of the spectrum may have its vibrations damped through a wide range of wave-length, provided the depth or density of the radiant layer be sufficient. The wide bands thus produced resemble those limited spectral regions within which certain phosphorescent solids and liquids radiate exclusively, but without giving definite line-spectra.

Strongly colored gases which absorb visible rays emit continuously in the same visible region of the spectrum. Mr. J. Evershed's experiments on the radiation of heated gases (*Phil. Mag.* (5), vol. 39, p. 465, 1895) prove "that besides iodine, the vapors of bromine, chlorine, sulphur, selenium, and arsenic can all be made more or less incandescent by heating to the temperature at which glass combustion-tube softens, and the light emitted by each of these glowing vapors appears to give a perfectly continuous spectrum, while the corresponding absorption-spectra are selective. Thus there is no such close relation between emission and absorption as is implied by Kirchoff's law of radiating bodies. There seems, however, to be a general relation between the total absorbing and radiating power for the visible rays."

The production of those distinct and widely separated vibrations which give line-spectra, demands considerable freedom of motion, such as exists in the partial vacuum of a Geissler's tube, in the high dilution of minute traces of metallic salts distributed through the mass of a Bunsen flame, or in the very thin surface layers at the inner and outer surfaces of such a flame, where chemical action is going on. Spectral differences are also found at different flame-levels, testifying to a succession of chemical interchanges which undoubtedly favor the production of line-spectra. Thus, cupric chloride in the Bunsen flame gives successive sheaths of yellow, red, blue, and green flame, due to metallic copper, cuprous chloride, and cuprous oxide, as Professor Smithells has shown by means of his cone-separator for studying the flame of the Bunsen burner. (*Phil. Mag.* (5), vol. 39, p. 122, 1895.) Very brilliant spectra of the copper salts may be obtained by means of a copper wire which has stood for some time in hydrochloric acid, and has become deeply corroded. There is also in this case a partial separation of the flame-effects as successive layers of the corroded film burn off.

The mechanism by which the discontinuous radiations of the electric glow in rarefied gases and of flames are produced has been the subject of much speculation. Werner Siemens, in 1882, wrote:

If we assume that the gas-molecules are surrounded by a sheath of ether, an alteration of these sheaths of ether must take place when two or more such molecules combine chemically. The resultant movement of the ether-particles must be compensated by vibrations which may form the starting point of the outflow of waves of light

and radiant heat. In quite a similar way we can picture the light-effects which appear when an electric current is passed through gases. (*Wied. Ann.* Bd. 18, S. 315.)

Since the current conducted by gas appears to be always accompanied by chemical action, the glow might be explained as in flames through the oscillating environment of the etherial sheaths of the gaseous molecules by which the passage of the electricity will be facilitated. (*Loc. cit.*, p. 316.)

Others have imagined the gaseous molecule to consist of a congeries of atoms whose configuration being changed by electrification, or during the act of chemical combination, for example, certain of the atoms being temporarily separated from their groups, or ionized, there results a series of atomic oscillations about a mean position, until the energy of the disturbance is dissipated as radiant energy of similar periods. As thus stated, this hypothesis offers no suggestion of the mode by which energy is transferred from the atoms to the ether. But if the gaseous molecule is composed of linked atomic vortices of ether, or of associated concentric vortices, in which are critical or limiting surfaces, conditioned by changes of form or velocity of etherial movement, the rearrangement of these groups determined by chemical interchange, or their disturbance from positions of equilibrium by electrification, may engender waves in the critical surfaces whose periods depend upon the dimensions and surface-velocities of these loci. The passage of systems of waves over such closed surfaces may give foci of interference, and it is possible that the connection and order observed in the frequencies of the numerous sorts of vibrations which the atoms of one element can execute simultaneously, or at least in such rapid recurrent succession that the series can not be distinguished from a simultaneous one, are to be thus interpreted.

The hypothesis of Arrhenius which assumes ionization of a gas wherever line-spectra are produced, demands a certain amount of ionic dissociation even at comparatively low temperatures, and this has perhaps not been demonstrated except under peculiar conditions of electrification; but whether, for example, we conclude as Liveing and Dewar did (*Proc. Roy. Soc. London*, vol. 30, p. 152, 1880; see also vol. 34, p. 418, 1882, where somewhat conflicting testimony is given), that the bands in the spectrum of the blue base of a Bunsen flame are due to carbon and hydrogen in the act of uniting or separating, in the formation or destruction of acetylene, the chemical union of these two substances being considered essential to the exhibition of this spectrum, or whether, with Lockyer and others, the spectrum in question be attributed to carbon vapor alone, I think we must agree with Arrhenius that it is an atomic rather than a molecular motion which produces the line-spectrum, and, in general, it is molecular motion which gives extensive diffuse bands, such as those of the absorption-spectra of liquids, and the absorption and emission spectra of some gases.

Is it necessary, however, that atoms should be completely free in order that their vibrations may give line-spectra? A distinction between the spectra of free and of partially constrained atoms may be granted, but it seems permissible to assume that some of the most persistent vibrations may be emitted by atoms in the midst of their aggregations which constitute the molecules. Prof. A. A. Michelson ("On the broadening of spectral lines," *Astroph. Journ.*, vol. 2, p. 251, Nov., 1895) finds that rarefied hydrogen (pressure about 1 mm.) gives out its characteristic spectrum under the action of an electric discharge at a remarkably low temperature. The width of a line having been proved to increase as the temperature rises in the ratio of the square roots of the absolute temperatures, the width of the red hydrogen line in an unheated tube was found to correspond to a temperature not more than 50° C. above the surroundings, or 320° absolute. The emission of *visible* radiations at such a low temperature implies that the rays are not produced by simple heating (molecular motion or rectilinear motion of free ions), but that the passage of the electric spark by ionic motions increases the motions (either rotations or oscillations) within the molecules, modifying the internal atomic motions without changing the rectilinear velocities of the atomic aggregates to any great extent. On the contrary, since hydrogen and other simple gases may be heated to very high temperatures without causing them to emit visible radiations, it is evident that the shocks produced by external collisions, due to rectilinear motions, are not as efficacious in setting up internal atomic vibrations as are the torsions experienced during the passage of a spark. The aurora is a case in point. In the middle latitudes it occurs usually at heights exceeding 40 miles, where the air is intensely cold, and is an instance of visible atmospheric radiation produced, not by direct thermal means, but electrically.

The experiments with dust-laden air have indicated that the addition of a small amount of solid matter, diffused through a large volume of air, does not change the radiating power of the latter perceptibly. The same conclusion may be drawn from the use of smoke to prevent frost, for if the finely divided carbon increased the radiating power of the air, the protection would be less effectual. The principal result which can be traced to the presence of floating dust is its modification of atmospheric transmission by the reflection and scattering of rays during their passage through the turbid medium.

Tyndall imitated the blue color of the sky, and even the peculiar polarization of its light—which is a maximum 90° from the sun, and which exhibits neutral points where the plane of polarization changes—by precipitating a mist of attenuated solid or liquid particles, of scarcely more than molecular dimensions, from mixed rarefied vapors capable of reacting chemically under the influence of light. By choosing substances, "*one* at least of whose products of decomposition under light shall have a boiling point so high that as soon as the substance is formed it shall be *precipitated*," solid or liquid particles of great fineness are produced without having time to cohere into coarser agglomerates. "By graduating the quantity of the vapor this precipitation may be rendered of any degree of fineness, forming particles distinguishable by the naked eye, or particles which are far beyond the reach of our highest microscopic powers." (*Contributions to Molecular Physics*, p. 431, from *Proc. Roy. Soc. London*, No. 108, 1869.)

As the particles become coarser they cease to reflect selectively, at least in the visible spectrum, but return light of every refrangibility in nearly equal proportion. In this way a cirro-stratus cloud spreads white light all over the sky, overpowering the blue light. In like manner a fog, dense enough to obscure the rays of the sun, may diffuse enough of sunlight to produce quite a bright general illumination; but in this case the reflection is not absolutely devoid of selective properties. To the palm of the hand held up, the position of the unseen sun is revealed through the sensation of warmth produced by solar rays of great wave-length which are capable of penetrating the mist. The obscure rays may also be recorded by the actinometer, and analyzed by the spectrobolometer, which shows that a mist, capable of keeping out all of the visible rays in the direct beam, may still transmit infra-red waves beyond $2\,\mu$ rather freely.

Lord Rayleigh (*Phil. Mag.* (5), vol. 47, p. 375, 1899) finds that diffraction from the molecules of the air, which are of small dimensions relatively to the waves of light, is competent to account for a large part of the selective scattering of short waves in sky-light, and for the actual transmission of the visible part of the spectrum. If x is the distance through which light must pass in air at atmospheric pressure before its intensity is reduced in the ratio of the basis of natural logarithms to unity,

$$x = \frac{3\,n\,\lambda^4}{32\,\pi^3\,(\mu - 1)^2}$$

where n is the number of molecules in the unit of volume, or $19 \times (10)^{18}$ per cubic centimeter according to Maxwell, μ is the refractive index as modified by the spherical molecules, $\mu - 1 = .0003$, and λ is the wave-length of light. Taking Bouguer's estimate of the transmission of star-light by an entire atmosphere, namely 0.8, we find, since the maximum sensitiveness of the eye for light as faint as that of the stars is about at wave-length

$$\lambda = 5 \times (10)^{-5} \text{ cm.},$$
$$x = 40 \text{ kilometers.}$$

The homogeneous atmosphere being 8.3 kilometers thick, the observed transmission by 40 kilometers is:

$$\left(0.8\right)^{\frac{40.0}{8.3}} = 0.34$$

which does not differ much from the assumed transmission, $\frac{1}{e} = 0.37$.

If Bouguer's eye was most sensitive to yellow rays at $\lambda = 6 \times (10)^{-5}$ cm., $x = 83$ kilometers, and the corresponding observed transmission, $(0.8)^{10} = 0.11$, is less than a third of that computed by

the hypothesis of molecular diffraction, leaving a considerable part of the blue light of the sky to be supplied from other sources. There can be no doubt, however, that the exponent of λ should be larger than 4 at the blue end of the spectrum, and smaller than 4 in the infra-red, as Lord Rayleigh suggests (*loc. cit.*, p. 383). The formula, as it stands, gives for $\lambda = 0.293\mu$ a transmission by one atmosphere of 0.17, and for $\lambda = 1.0\mu$ a transmission of 0.99; but the former is known to be zero, and the latter, as far as it depends on selective scattering, is probably more nearly equal to $0.99 - 0.17 = 0.82$. The sudden termination of the solar spectrum at 0.293μ may be produced by a local absorption-band of oxygen, but selective scattering gives nearly the same limit.

Cornu (*Comptes rendus*, t. 88 and 89) finds that the limit of atmospheric transmission in the ultra-violet with a clear sky, depends on the barometric pressure, thus on the oxygen and nitrogen contents, rather than on aqueous vapor or other variable constituent of the air. If it were not for this fact it might be supposed that the molecules of water-vapor, or the products of condensation resulting from the continual diffusion of a very rare aqueous vapor into the upper atmosphere, might be the sole cause of sky-color, since, as Tyndall remarks (*Heat as a Mode of Motion*, p. 414), "the color of the firmamental blue, and of distant hills, deepens with the amount of aqueous vapor in the air," and in part this may be an additional cause of coloration, although it appears to be of no importance in determining the limit of the spectrum. The association of the deepest blue sky with the descending air of the tropical calms may be explained by the purification which the air has undergone. The coarser dust having been washed out in the abundant precipitation of the equatorial rains, the genuine color of the sky resulting from molecular diffraction is no longer obscured by the more general scattering of light by the larger and unassorted particles.

The beautifully colored coronas and patches of color seen upon incipient cirrus near the sun are due to diffraction from ice or water particles of a coarser order than the molecular, and graduate into cases of simple and indiscriminate reflection from still coarser particles, an effect which becomes very great at large angles of incidence, and produces the strong glow around the sun, never absent except in a sky of exceptional purity, such as can only be found at great altitudes.

Whymper in his *Travels Amongst the Great Andes of the Equator*, page 324, thus describes the effect of clouds of volcanic dust from Cotopaxi:

> When they commenced to intervene between the sun and ourselves the effects which were produced were truly amazing. We saw *a green sun*, and smears of color something like verdigris green high up in the sky, which changed to equally extreme blood-reds, or to coarse brick-reds, and then passed in an instant to the color of tarnished copper, or shining brass. No words can convey the faintest idea of the impressive appearance of these strange colors in the sky—seen one moment and gone the next—resembling nothing to which they can properly be compared, and surpassing in vivid intensity the wildest effects of the most gorgeous sunsets.

I think there can be no doubt that these vivid colors were entirely due to diffraction, owing their brilliancy to the uniformity in the size of the particles producing them. The description reminds one of the colors of soap bubbles in sunshine. Cirrus clouds are apt to be composed of ice crystals in the act of forming from vapor. The particles are constantly growing in an irregular way, and numerous diffraction rings produced by means of swarms of particles of as many different diameters, are superimposed, so that the blended colors are not pure, and there is much white light.

In general, a part of the diminution of solar rays in passing through the air is due to selective scattering by air-molecules, to which diffraction by ice-crystals of minute size, and reflection from dust of every sort may be added in a hazy atmosphere; but these causes have very little influence upon the true atmospheric radiation which consists chiefly of long waves but little affected by dust.

SUMMARY.

The exposition of a few leading principles is needed to give entrance and guidance in a general survey of the subject. Atmospheric radiation is so extensively modified by atmospheric absorption of rays that the subject of the atmosphere's transmissive power must be included.

The atmosphere by its molecular constitution produces a selective scattering of the rays which pass through it, which is greatest for the short waves. Ether-waves of greater length than 2μ are but little affected by selective scattering, but throughout the visible spectrum there is an

increasing depletion of the direct radiant beam, progressing a little more rapidly than the inverse fourth power of the wave-length. The rays taken out of the direct beam in this way do not alter the temperature of the air, and a large part of them reach the Earth's surface. The same is the case with the light diffracted by minute ice-crystals, or more indiscriminately reflected by coarser dust-particles.

An entirely different process is involved in the production of local line and band absorption. Special rays are absorbed by the atoms and molecules of the various atmospheric constituents. Here the energy which exists in the ether as radiation is transformed into the energy of molecular or atomic movement, and remains in the atmosphere as an increase either of its sensible temperature or of its latent heat. The ultra-violet rays appear also to produce chemical change in some of the atmospheric substances, accompanied by electrification. The composition of the atmosphere is being continually changed by emanations from the Earth and its inhabitants, and the atmospheric thermal energy is increased in this way, and especially by the latent heat of vaporization of water. Heat is also developed dynamically whenever there are descending movements in the air. High winds in dry and dust-laden air generate large amounts of frictional electricity, and a part of this thermal and electrical energy imparted to the air from many sources, is eventually given out again in the form of radiation.

The actual spectral energy-curve of a depleted sunbeam is a complex of an exceedingly variegated original radiant energy, as further modified by telluric absorption, every one of whose lines and bands has a separate origin and law of variation. In like manner the radiation emitted by the air is made up of a great variety of individual lines and bands, each having a law of its own, depending on the pressure, depth, temperature, and physical state of the productive constituent. In a measure the emission by the air resembles its absorption, but is confined to the longer waves when thermally produced at relatively low temperatures. Unknown regions in which the oxygen, nitrogen, argon, and krypton of the atmosphere radiate at low temperatures, remain to be explored. The chief radiations which can now be definitely placed in the spectrum are those of aqueous vapor and carbon dioxide. Owing to the feebleness of these radiant bands at low temperatures, the positions and relative intensities of the more refrangible ones are best studied in the absorption-curve of the solar spectrum.

The following table (75) of positions and intensities of infra-red bands in the solar spectrum has been compiled from two plates—(*a*) *A* to ω_2, (*b*) ω_1 to deviation 38° 45′—accompanying an article on the "Infra-red solar spectrum of a 60° rock-salt prism," published in the *Annual Report of the Smithsonian Institution* for 1897, Appendix V, pp. 66–68. The standard temperature of the prism is stated to be 20° C. "The positions of about 225 absorption lines and bands are determined * * * between deviations of 40° 25′ and 38° 45′, corresponding to wave-lengths 0.76 μ and 5.20 μ, respectively." These curves are the culmination of Langley's long labors in the solar spectrum. No band is included in the present list which is not also shown on the three bolographs exhibited by Professor Langley at the Oxford meeting of the British Association (*Astrophysical Journal*, vol. 1, p. 162, pl. 9, Feb., 1895). The numbers assigned here to the intensity of absorption at the centers of the individual bands have been obtained by comparing the bolographic ordinates with those of a smooth curve passed by estimation through the unabsorbed maxima. A list of these maxima and their intensities in the prismatic spectrum follows:

TABLE 74.

Minimum deviation.		Intensity of radiation.	
°	′		
40	24.5	11	[14]
40	9.0	24	[28]
39	56.4	38	[45]
39	47.0	54	[64]
39	38.0	63	[77]
39	28.5	31	[62]
39	12.0	18	[36]

The numbers in brackets are the values obtained by correcting for atmospheric absorption. The adopted curve has been made symmetrical on the side of greater wave-length to allow for the undoubtedly very large absorption of the entire spectrum as the great bands of water-vapor and carbon dioxide are approached, since in this region the intervening points of comparatively unabsorbed energy begin to be encroached upon by the bands. The corrected values have been assigned after taking account of the extensive stretch of almost total absorption between 5 μ and 8 μ, and the probable form of the original spectral energy-curve before the radiation entered the Earth's atmosphere has been inferred by supplying these missing regions. The limits adopted for the breadths of the bands and groups of bands are somewhat arbitrary, owing to the very gradual way in which the slopes of the energy-curve begin:

TABLE 75.

Designation of band.	Minimum rock-salt deviation.	Wave-length.	Transmission.	Absorption.	Wave-lengths assigned by other observers.	Source and remarks.
	° ′	μ	*Per cent.*	*Per cent.*		
Great A	40 24.0	0.76	1÷14.2= 7.0	93	Abney.	Telluric.
A_1	40 23.6	0.77	2÷14.5=13.8	86	Photography. Diffraction grating.	Oxygen.
Brewster's Y_1	40 16.7 to 15.5	0.82	10÷20.6=48.5	52	.816–.821	Includes solar Na .818.
" Y	40 15.3	0.825	8÷21.3=37.6	62	.823	
" X_3	40 15.0 to 13.5	0.83	9÷22.4=40.2	50	.825–.832	
" X_1	40 12.2	0.855	16÷24.6=65.0	35	.854	Solar Ca.
" X	40 11.7	0.86	15÷25.2=59.5	40	.866	Solar Ca.
	40 10.5	0.875	20÷26.4=75.8	24		Telluric, probably aqueous.
	40 7.7 to 6.6	.895– .91	18÷30.0=60.0	40	.895–.903	Telluric, probably aqueous.
Abney's π	40 6.6 to 6.0	.91 – .915	18÷30.9=58.3	42	.905–.911	Telluric, probably aqueous.
	40 6.0 to 5.2	.915– .92	18÷31.8=56.6	43	.912–.918	Telluric, probably aqueous.
Rho-tau group	40 4.6 to 39 59.5	0.925 to 0.985				Breadth, 0.060μ.
Abney's ρ	40 4.6 to 3.5	.925– .935	6÷33.4=18.0	82	.930–.939	Telluric, probably aqueous.
" σ	40 3.5 to 1.3	.935– .965	8÷35.7=22.4	78	.943–.950	Telluric, probably aqueous.
" τ	40 1.3 to 39 59.5	.965– .985	23÷38.4=59 9	40		Telluric, probably aqueous.
	39 58.7	1.00	32÷41.4=77.3	23		Telluric, probably aqueous.
	39 54.8	1.06	37÷48.3=76.6	23		Telluric, probably aqueous.
Great phi group	39 53.7 to 39 47.0	1.085 to 1.24				Breadth, 0.155μ.
Abney's Φ	39 53.7 to 51.6	1.085 to 1.125	9÷52.7=17.1	83		Telluric water vapor.
	39 51.6 to 51.1	1.125–1.13	11÷55.0=20.0	80		
	39 51.1 to 49.8	1.13 –1.16	13÷56.9=22.8	77		Includes solar Na 1.132.
	39 49.3	1.17	39÷59.4=65.7	34		
	39 48.5	1.19	43÷60.9=70.6	29	Grating and spectrobolometer.	
υ	39 46.5 to 45.2	1.25 –1.28	45÷66.0=68.2	32	Paschen.	
Great psi group	39 45.0 to 39 38.2	1.28 to 1.52			Bunsen flame, 1.33μ to 1.50μ.	Breadth, 0.240μ.
	39 43.7	1.32	29÷70.9=40.9	59		Telluric water vapor.
Abney's Ψ	39 43.0 to 41.0	1.34 –1.40	4÷73.4= 5.4	95		Telluric water vapor.
	39 40.8	1.405	8÷75.0=10.7	89		Telluric water vapor.
	39 39.9	1.44	16÷76.1=21.0	79		Telluric water vapor.
	39 37.5	1.54	58÷76.8=75.5	25		Telluric water vapor.
	39 36.8	1.57	58÷76.4=75.9	24		Telluric water vapor.
	39 36.1	1.59	58÷75.9=76.4	24		Telluric water vapor.
Great omega group	39 34.8 to 39 28.5	1.65 to 2.03			Bunsen flame, 1.75μ to 2.10μ.	Breadth, 0.370μ.
Langley's Ω	39 33.0 to 30.8	1.75 –1.87	1÷66.4= 1.5	99		Telluric water vapor.
" ω_1	39 30.3 to 29.6	1.91 –1.97	9÷65.0=13.8	86		Telluric water vapor.
" ω_2	39 29.6 to 28.5	1.97 –2.03	21÷63.0=33.3	67		Telluric water vapor.

TABLE 75—Continued.

Designation of band.	Minimum rock-salt deviation.	Wave-length.	Transmission.	Absorption.	Wave-lengths assigned by other observers.	Source and remarks.
	° ′	μ	Per cent.	Per cent.		
Great chi group	39 28.0 to 39 11.5	2.08 to 3.48			Bunsen flame, 2.42μ to 3.02μ.	Breadth, 1.400μ. H_2O+CO_2.
Langley's X	39 23.7 to 17.9	2.36 –2.86	1–49.0= 2.0	98		
" χ_1	39 17.2	2.92	3÷43.5= 6.9	93		Telluric water vapor.
	39 16.4	2.99	3÷42.5= 7.1	93		
	39 15.9	3.02	9÷41.7=21.6	78		
" χ_2	39 15.0	3.10	3÷40.3= 7.4	93		
	39 14.3	3.15	5–39.3=12.7	87		
	39 13.8	3.20	4÷38.6=10.4	90		
	39 13.2	3.24	7÷37.8=18.5	82		
	39 12.6	3.29	12÷36.8=32.6	67		
	39 11.3 to 10.7	3.41 –3.46	14÷34.5=40.6	59		
	39 10.7 to 9.6	3.46 –3.53	14÷33.3=42.0	58		
	39 9.1	3.58	11÷31.8=34.6	65		
	39 7.0 to 6.3	3.73 –3.80	9÷29.0=31.0	69		
	39 6.3 to 5.5	3.80 –3.87	9÷28.2=31.9	68		
Great upsilon group Υ	39 5.5 to 38 55.0	3.87 to 4.60			Grating and spectrobolometer, Paschen. Bunsen flame, 4.15μ–4.39μ.	Breadth, 0.730μ, telluric carbon dioxide.
	39 2.0 to 38 56.5	4.12 to 4.43	1÷21.4= 4.7	95		

The great bands of which the radiation of the atmosphere at slight excess of temperature mainly consists, lie in the infra-red spectrum beyond the limit of this table. Fig. 21 is a provisional spectral energy-curve of the radiation of moist air for the temperature + 50°C. The positions of the bands rest upon the observations of Paschen, Rubens, and Aschkinass, and relate to the emission

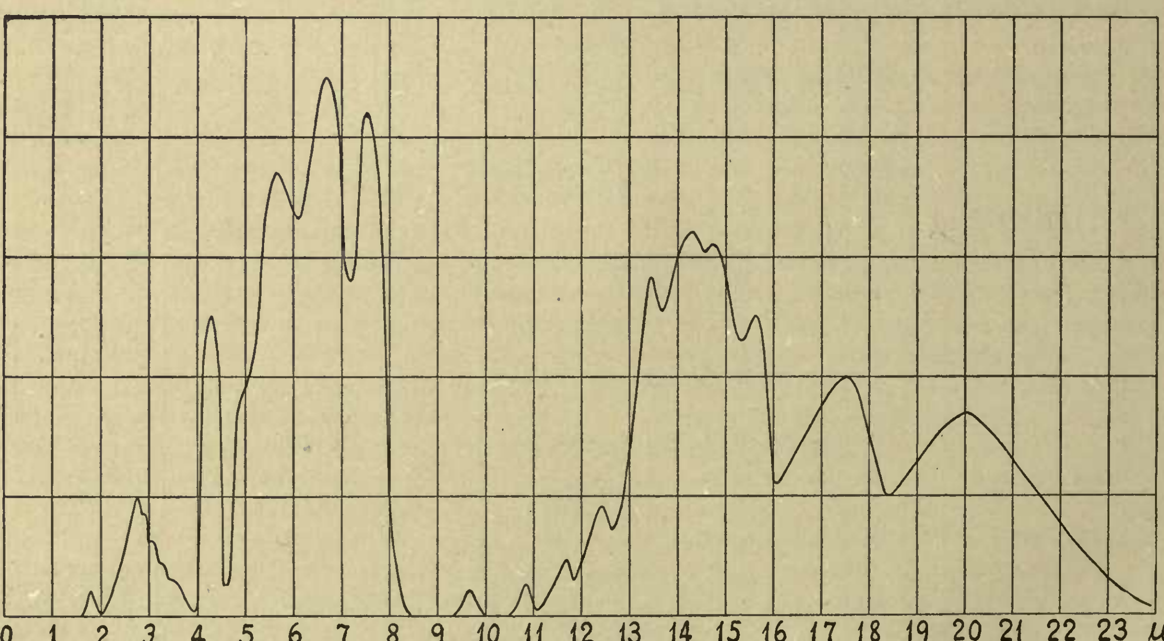


Fig. 21

Approximate spectral energy-curve of air radiation.

from aqueous vapor and carbon dioxide, with the exception of the radiant energy of extreme wave-length, which I have provisionally assigned to one or more of the permanent gases, nitrogen, oxygen, etc., on the strength of Hutchins' observation of the absorption of air radiation by quartz.*

* See p. 112.

The form of the curve will vary according to the temperature and composition of the air. The relative heights of the maxima are assumed to vary inversely as the absorption, but some deviation from this rule must be anticipated. Similar curves for depths of air giving maximum radiant efficiency at the principal bands may be constructed for other temperatures by first drawing the appropriate energy-curve for a black body, and then inserting and graduating the heights of the radiation-bands, so that the highest may be included by the curve.

It has been explained that a considerable part of the radiation of short wave-length diffused by the dust and finer particles of the atmosphere, reaches the surface of the earth.* Not so, however, that portion of solar radiant energy which has suffered the special absorption which causes the cold bands of the infra-red spectrum. This energy remains in the air as an increase of temperature, and is subsequently lost again as atmospheric radiation; but since the greater density and humidity of the surface air obstructs downward radiation, and since, further, in any radiant interchange which can proceed through the deeper and denser layers the excess of expenditure is in the hotter air, which is usually beneath, it follows that atmospheric radiation, with rare exceptions, proceeds mainly outward.

Suppose that one-fifth of the entering radiation remains behind in a layer of air 20 kilometers deep. Then during one hour in the middle of the day, the solar constant being 0.05 radim, $\frac{1}{5} \times 0.05 \times 3600 = 36$ small calories will be imparted by the sun to each column of 1 sq. cm. section and 2,000,000 cm. high. The upper layers have the opportunity of attacking an unsifted sunbeam and of taking out those rays at the band-centers which are totally absorbed by very small quantities of matter. Hence in spite of the rarefaction of the air and of its chief absorbent at high altitudes, the absorption per unit of absorbent material being very much greater at the start, the actual distribution of absorption at different altitudes may be tolerably uniform. If the heat developed in the extinction of solar rays is distributed uniformly through the entire 20 kilometers, each kilometer receives 1.8 small calories in a vertical column of 1 sq. cm. section during one hour in the middle of the day, and the consequent elevation of temperature is 0.7° C. at an altitude of 20,000 meters, but only 0.07° C. at a height of 1,000 meters. The upper part of the first layer, because it receives the undepleted rays, will continue to absorb with the same intensity during the hours of sunshine, and the entire layer on account of the obliquity of the rays and longer paths with a low sun will absorb more powerfully as the sun's altitude diminishes, and at the equinoxes might have its temperature raised at least 8.4° in one-half day if none of the heat were lost; but as the losses certainly exceed the gains, the diurnal range is not likely to be more than one-half of this amount.

The deeper layers of air receive solar radiation which has been depleted of its more absorbable rays, and as the sun nears the horizon a relatively larger part of the energy remains in the upper air, whence the lowest layers may not be heated in one-half day more than four or five times as much as in one hour at midday, and the diurnal range of temperature due to absorption of solar rays probably does not exceed two or three tenths of a degree in the 2 or 3 kilometers of air above the surface. Very much larger ranges occur in the first 1,000 meters from the ground, but they are due to ascent of air heated by contact with the soil and cease at an altitude of about 1,000 meters, where the lower cumulus clouds mark the upper limit of this convection. (See "Exploration of the air by means of kites" at the Blue Hill Meteorological Observatory, *Ann. Harvard Coll. Astron. Obs.*, vol. 42, part 1, p. 103, 1897.) Only in case the previous sifting had deprived the sunbeam of all of its absorbable rays, or provided the thermal energy were lost by reradiation as fast as it is received, could there be a complete absence of thermal effect.

The advancing part of an anticyclone receives air directly depleted of moisture in the preceding area of precipitation. The dry air is a bad radiator, and the full increment of temperature by compression in the descending air is preserved. Hence the adiabatic rate of cooling in unsaturated air with increase of altitude is maintained or exceeded in the front part of the anticyclone, as Clayton has observed (*loc. cit.*, p. 118). But in the western part of the anticyclone and the advancing region of a following cyclone the greater easterly velocity of the upper air carries along

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* See the previous chapter on atmospheric dust, p. 118.

an overhanging mass of warm, moist air which diminishes or reverses the upward fall of temperature. The alternation of hot and cold waves in winter brings a considerable range of temperature in the lower air which must not be confounded with that produced by the direct absorption of solar radiation.

The depth of 20 kilometers has been taken as defining somewhat approximately the part of the atmosphere within which water-vapor can exist in appreciable quantities or what may be called the aqueous atmosphere.

It is evident, after what has been said in regard to the small depth from which atmospheric radiation can pass freely, that radiant emission from so great a depth of air as 20 kilometers, or even from a small fraction of a kilometer, can only take place by the slow process of one portion of air radiating to a neighboring one which is at a slightly lower temperature, and this in turn to other volumes not far away, the process being repeated over and over again until the upper regions of freer transmission are reached.

The curve of transmission of radiation by the terrestrial atmosphere, given in fig. 22, is intended to represent only the most important features. It relates to a vertical transmission through a clear air of only moderate humidity, and includes (1) the general fact of selective scattering of short waves, (2) the progressive strengthening of band absorption in the infra-red,

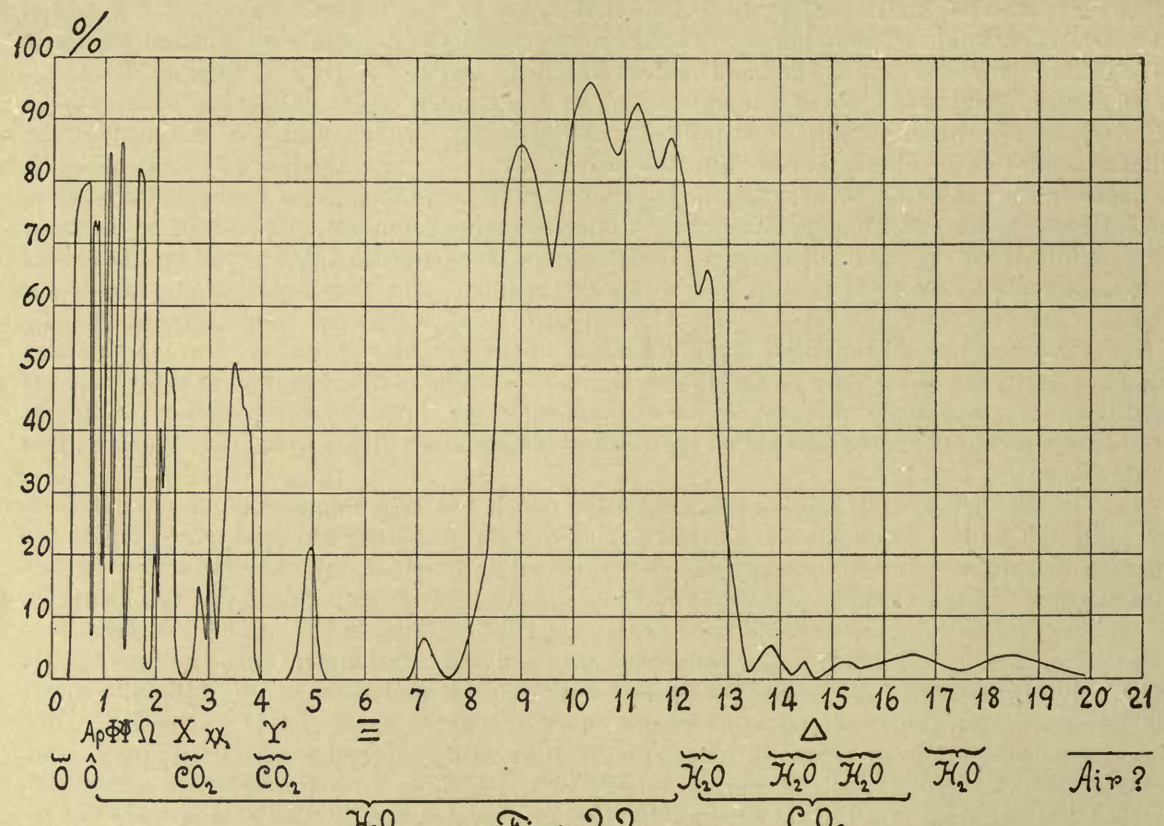

Fig. 22

Transmission of radiation by the Earth's atmosphere.

due mainly to water-vapor, including bands at 0.95μ, 1.1μ, 1.4μ, 1.9μ, 2.5μ, and 4.7μ, until (3) the great bands of this substance between 5μ and 8μ, marked Ξ in the figure (strongest absorption at 5.9μ, 6.5μ, and 7.5μ), are reached, (4) the greater but decreasing transmission beyond 9μ with absorption-bands at 9.6μ, 10.9μ, 11.6μ, 12.4μ, 13.4μ, 14.3μ, 15.7μ, 17.5μ, and perhaps at 20μ, still attributable to aqueous vapor, with the exception (5) of a wide band extending from 12.5μ to 16μ with a maximum of absorption at 14.7μ, denoted by $\triangle$ in the figure, which with the band at 4.3μ and the smaller one at 2.7μ, is produced by carbon dioxide, and finally (6) a region of almost total absorption beyond 20μ, here provisionally attributed to the permanent gases of the atmosphere.

The absorption by carbon dioxide, by water-vapor, and possibly also by the permanent gases, practically obliterates the solar spectrum beyond 13 μ, since the unabsorbed radiation is here very feeble.

Some of the consequences of atmospheric absorption may be briefly pointed out. The absorbent action of carbon dioxide and the permanent gases is almost invariable; but the absorption bands of aqueous vapor are much stronger in summer than in winter, and the selective scattering of short waves also increases in summer. One result of this variation is that the direct rays of the midday sun, received upon a normal surface, are more powerful in winter than in summer, in spite of the greater distance traversed by the sunbeam through the air in winter. Dr. Emil Bessels* noted that the rays of the arctic sun in early spring, although making a very small angle with the horizon and penetrating a great depth of air, affected the actinometer much more intensely than later in the season after the sun had risen higher, but when the air had become moist.†

The direct effect of the sun's rays upon a normal surface is less in the tropics than in temperate regions, and less at sea level than upon a mountain top, owing to the difference in the aqueous component of the air; and the ability of the solar radiation to maintain a high temperature in the torrid zone or at sea level is due to the accumulation of the thermal energy imparted to the Earth's surface by reason of the retention of the escaping radiation from that surface by a moist and highly absorbent atmosphere rather than to the direct power of the sunbeam. The position of the great water band (Ξ in fig. 22) covers a region of the infra-red spectrum in which terrestrial radiation is near its maximum, and the emission from the soil is still strong at the great Δ band; but the sun's rays are most powerful in the visible spectrum where aqueous absorption is small and the bands of carbon dioxide completely lacking. Thus the penetrative power of the incoming is greater than that of the outgoing rays, and this relative difference, which increases with the amount of moisture in the air, produces an accumulation of thermal energy at the Earth's surface, which would generate a very high temperature were it not that the sign of the function is reversed after sundown. The cumulative effect of continuous sunshine gives a mild summer to the arctic regions with a sun of lower altitude than that which brings vigorous winter weather in lower

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* *Scientific Results of the U. S. Arctic Expedition. Steamer Polaris.* Vol. I, Washington, 1876. § Solar Radiation, pp. 80–82.

† In Lieutenant Ray's *Report of the International Polar Expedition to Point Barrow, Alaska* (Washington, 1885), differences of black and bright bulb thermometers are given for this station between February 1 and August 27, 1883. During the month of March differences above 45° F. were measured on twelve days, during April on fourteen days, during the first half of May on seven days; but after this the differences did not again reach 45°. In June a difference greater than 40° was only attained on three days, and during July and August the excess of the black bulb did not once reach 40°. This sequence of low readings is no doubt partly due to the greater cloudiness of the summer months, for the black-bulb thermometer requires time to reach a maximum reading which often fails to be recorded during the brief intervals between clouds. Nevertheless, the highest reading of all, 82°.3 F., being made on the 8th of May, which has its parallel in the frequent maximum reading at 9 or 10 a. m. in a diurnal curve of intensity, confirms the result of Dr. Bessels, and with many other similar facts, proves that altitude of the sun above the horizon is not the only important factor conducing to intense solar radiation.

The reader may also consult the *Report on the Proceedings of the U. S. Expedition to Lady Franklin Bay*, by Adolphus W. Greely, vol. 2, p. 377, Chart No. 17 (Washington, 1888). The curve of solar radiation attains its maximum in May, and it is noted that "the effect of increasing humidity or aqueous vapor in intercepting the solar [radiant] heat is shown in a most marked manner."

These observations of solar radiation were made with conjugate bright and black bulb thermometers in vacuum chambers of glass, an instrument which, as we now have it, is not capable of giving accurate quantitative values. The chamber is supposed to be a vacuum, but there is usually no means of verifying the supposition. Minute quantities of certain vapors, condensible at low temperatures but evaporated in hot sunshine, may alter the indications widely. If it is desired to get rid of all convection and penetration of gaseous molecules within the envelope, a very perfect vacuum must be obtained, and variations either in the degree of exhaustion or in the material of the transmitting walls will produce serious discrepancies in instruments exposed side by side. Glass also does not transmit the longer radiations readily, and the amount rejected will vary with the thickness and quality of the glass, with the nature of the surrounding surfaces, and especially with the previous depletion in passing through the atmosphere, which is the very thing we are seeking. A part of the heat registered comes from short-waved sky reflection, and this is relatively greater with a low sun; nevertheless the existence of an absolute low-sun maximum radiation can not be thus explained, and since the chief defect of the instrument is that it shuts out much of the radiation of long wave-length and obscures its variation, it is quite possible that a perfect actinometer would show as great or greater seasonal fluctuations.

latitudes, continuity of accumulation more than compensating the advantage of greater transmission in winter.

The heat entrapped through the differential transmission of solar and terrestial radiation by aqueous vapor and carbon dioxide is mainly stored in the lower layers of the atmosphere, and because the absorption by air heavily loaded with moisture is nearly complete for its own radiation, this stored-up energy continues for a long time as a controlling balance wheel in the mechanism of the weather. As long as the mantle of water vapor remains unbroken, thermal fluctuations are kept within narrow limits. Storms may make inroads upon the continuity of this aqueous atmospheric envelope, but evaporation of moisture restores the rents. Rolled up in great bosses covering hundreds of thousands of square miles of territory, the thickened mantle of vapor brings hot waves. Displaced by downward movements bringing the dry air of the upper atmosphere to the surface, corresponding cold waves result. The gradual accumulation of moisture in higher and higher atmospheric layers during the summer, clothes the temperate regions with so deep a protective covering of moist air, that summer conditions are prolonged in the autumn to a time which is astronomically the correlative of late winter. The absence of this deep protective layer, whose formation can only be effected gradually, permits late frosts in spring, long after the sun has resumed his ascendency. In the middle of a sunshiny day, by the evaporation of moisture from the earth's surface and its ascent in convection currents, the vapor of water is carried up to high levels; but during the night most of this accession of moisture is diffused into colder or drier regions of the upper air, where it is either condensed and no longer exists in the air as vapor, or is so diluted and reduced in relative humidity as to be of slight absorptive value when the sun next rises. The increase of moisture in the upper air at midday is the cause of the flat-topped diurnal actinometric curves which are observed on all but the coldest and driest days. As the sun mounts above the horizon, the intensity of his rays augments, giving an actinometric curve, which, on an exceptionally dry day, is approximately a parabola, symmetrical about the midday ordinate; but, in general, the apex of the curve is truncated, and after about 9 a. m. the curve becomes flat-topped with minor fluctuations indicating the activity of the convective process, and the passage of invisible clouds of vapor across the line of sight. At the same time the curve of relative humidity of the surface air becomes deeply depressed, while at high levels the tension of aqueous vapor increases in the middle of the day, indicating the rapid removal of aqueous vapor from the lower to the upper air. The earth has its lowest temperature and the air, if clear, its greatest transmission in the early morning hours when, as a whole, the atmosphere, according to observations at high levels, has its smallest content of aqueous vapor, a condition which is evidently correlated with the maximum actinometric effect observed by Bessels in the arctic spring months.

It appears certain that on our Earth surface temperatures lower than $-73°$ C., or $200°$ absolute, can not occur, possibly because of the almost total absorption by the atmosphere of all radiations beyond 13μ. Paschen's law of the wave-length of the maximum in the normal spectral energy-curve of a black body gives at this temperature:

$$\lambda\ max. = \frac{2891}{200} = 14.46\mu.$$

Thus the position of the normal maximum in the energy-curve for the lowest arctic temperature very nearly coincides with the great absorption-band of carbon dioxide ($\varDelta$, fig. 22), discovered by Rubens and Aschkinass; and at lower temperatures the maximum would be found at still greater wave-lengths on which the permanent gases of the atmosphere may possibly exercise a complete absorption. In the midst of much conflicting testimony as to the region of the spectrum in which the absorption of pure air resides, this suggestion is at least worthy of consideration.

By the same law a sunlit surface of rock at $340°$ absolute temperature, if radiating like a black body, must have its spectral maximum at 8.5μ; and taking the mean temperature of the earth as $+15°$ C., its spectral maximum would reside on the average at 10μ. Some deviation from the law is to be expected and does occur in the spectra of solids, which do not conform to the ideal of blackness. Since it appears to be a general law that the radiation of a body is especially large in that spectral region where its absorption is exercised, it is possible that the radiation of the ocean at a mean surface temperature of $+15°$ C. will be found to have the maxi-

mum in its spectral energy-curve displaced to a wave-length shorter than 10μ, and approaching the great band (Ξ) where the absorption of atmospheric moisture is greatest, and that this is another cause, in addition to the large specific heat and mobility of water, conducing to the slowness of oceanic temperature changes; but more important as a retainer of oceanic heat is the extension of the band Ξ to greater wave-lengths in the absorption of the layer of air nearly saturated with moisture, which always hangs over the water.

The absorption of terrestrial radiation by atmospheric moisture lies somewhere between such curves as those of figs. 14 and 15. Aqueous absorption is very greatly increased as the air approaches saturation, because the molecules of water-vapor then become complex and have an absorptive power approaching that of liquid water.* The absorption of the atmosphere and the surface temperature which can be maintained by its aid, increase both with the absolute and with the relative humidity.

Not only is the absolute temperature of the soil dependent upon atmospheric moisture, acting in conjunction with the heat supplied by the sun's rays, but also the diurnal range of surface temperature. "Where the land is moist the changes of temperature are less than where it is dry or arid," but it is the condition of the air and not that of the soil which makes the radiation possible or impossible. The following illustration under nearly the same insolation must suffice as an example.

After several weeks of rain in May, the daily range for the first week of pleasant weather in June was 9°. 5 C. At the beginning of August, after two months of drought, the range had increased to 12°. 1 C., and the highest range of the week in June (10°. 4 C.) was less than the lowest (10°. 6 C.) of the week in the time of greatest drought.

TABLE 76.

Date.	Range.	Sky.	Date.	Range.	Sky.
	° C.			° C.	
June 3	8.8	Clear—Cirrus.	July 31	11.0	Clear, smoky—Cirrus p. m.
" 4	10.4	Alto-cumulus—showers.	Aug. 1	11.9	" " cloudy evening.
" 5	9.2	Cloudy—Rain.	" 2	11.2	Cloudy, 0.01 inch of rain.
" 6	8.8	Cloudy a. m.; clear p. m.	" 3	12.8	Cumuli.
" 7	10.4	Cirrus—Cumuli p. m.	" 4	14.5	Clear, then cumuli.
" 8	9.5	Clear—Hazy.	" 5	10.6	Clear.
" 9	9.1	" "	" 6	12.4	Clear—Smoky.
Mean.	9.5		Mean.	12.1	

On Pike's Peak the range is greater in winter than on the plains, but less in summer. Here also the mountain climate is relatively drier than that of the plains in winter than in summer.

In free air the diurnal range is small, but in this case because the radiation which has escaped the previous action of the chief absorbent of radiation, water-vapor, is deficient in absorbable rays, and small toll is taken by the air. On a mountain, and still more on a plateau, the increased power of the sun's rays heats the rocks, and thence the surface air, more than at lower altitudes, and unless the wind is so strong as to remove the surface air before it is much heated, replenishing it with cool air from the free atmosphere around the mountain top, the range may be greater on the mountain than on a low-lying plain, because of the more powerful insolation.

The spectrum of the radiation of the atmosphere consists entirely of lines and bands; and since the atmospheric absorption acts within the same limited regions of the spectrum, atmospheric radiation is largely annulled by an absorption which is identical in quality, or as to the kinds of rays affected, with the thing on which it is exerted, and can differ only in regard to the rapidity with which extinction or emission vary with the depth, or by a redistribution of energy, according to which the radiation in process of transmission may be absorbed by one constituent of the atmosphere but emitted again by a different one, or passed on by a series of alternate radiations and absorptions. In any case the depth from which atmospheric radiation can directly proceed is

* See p. 100, *et seq.*

limited, and the amount of the emission is relatively greater for a small depth. Hence laboratory experiments which deal with small layers of air, give radiant values which are too large to be applied without discrimination in meteorological problems.

Owing to the feebleness of the radiation-bands in the spectrum from air at such moderate temperatures as prevail in the atmosphere, and owing further to the limitation of the emission to the outer layers of large masses of air, small effect is to be anticipated from the radiation of elevated bodies of warm air to a cooler underlying surface. Clayton's kite experiments on Blue Hill have demonstrated the existence of high warm layers of clear air above cold layers and a cold surface, when the surface winds are from a cold quarter, and when the surface temperature has been changed very little by the substitution of warm for cold air at the upper level. Radiation effects are immediate, and it is possible that under these circumstances a slight elevation of temperature from the radiation of the warm air may be discriminated in advance of the slower rise of temperature produced by the commingling of air currents and the bodily transfer of superficial air from warmer regions by cyclonic movement. The most advantageous occasion for testing such a possibility is immediately after a severe cold wave in winter, for then the absorbent power of the lower air for the hypothetical radiation from the warm upper layer will be least. The return of an elevated body of relatively warm air after a severe cold wave is usually heralded by an increase of cirro-stratus cloud, and this alone may make surface temperature greater by the action of the aqueous vapor whose presence is made known by the cloud, the vapor imprisoning more of the sun's rays in the daytime, and impeding the escape of terrestrial radiation at night.

I will give two examples of recovery from cold waves, observed at Providence, R. I., taking the data from the records of the City Engineer's Office and of the Ladd Observatory.

Cold wave of January 6 to 10, 1896.—The minimum of $-8°$ F. on the morning of the 6th was followed by a gradual recovery, lasting four days. Each day saw a recovery of about 7°. The air on the 6th was very dry (relative humidity 22 per cent.). The barometer, which had risen to 30.37 inches on the evening of the 6th, fell very slowly to 29.81 inches on the morning of the 10th. In this case there was no pronounced cyclone, but 3 inches of snow fell from 2 p. m. on the 7th to 2 a. m. on the 8th, and 11 inches from 3 p. m. on the 9th to 7 p. m on the 10th. The clouds began to gather on the morning of the 7th. The wind continued north during the four days, except for a short time on the 9th.

Cold wave of February 16 to 19, 1896.—There was a fall of 2.5 inches of snow, ceasing at 3 p.m. on the 16th. The thermometer, which at 0 a. m. on the 16th was 42° F., fell steadily to $-8°$ F. on the morning of the 17th. The highest temperature on the 17th was $+7°$ F. at 5 p. m. after a day of unclouded sunshine. The barometer, after 7 a. m on the 17th, was steady at 30.30 inches. Relative humidity rose slowly during the night of the 17th to 18th from 40 per cent. to 55 per cent.; lowest temperature, 0° F. at midnight. Sky clear until the morning of the 18th, when there was a trace of snow (clouds 0.9); temperature $+2°.5$ at 6 a.m., February 18th, and barometer falling (30.20 inches). Relative humidity and temperature then increased rapidly, until at 11 p. m. snow began to fall, continuing until 9 p. m. on the 19th, when the barometer had descended to 29.27 inches. The wind continued north until noon of the 19th, when it changed to the southeast. Here a part of the rise of 10°.5 in the first twenty-four hours after the minimum must be attributed to the influence of sunshine. More rapid recoveries than this are almost invariably accompanied by a change of wind to the south, or by a sudden accession of moisture, implying the importation of warm air from a milder neighborhood.

The solar radiation of 0.05 radim often produces a rise of temperature of 15° C. between sunrise and midday (no account being taken of atmospheric absorption). A rise of temperature at the rate of 1°.5 C. in six hours after a cold wave may frequently be observed, indicating a radiation of 0.005 radim, if due to a warm upper layer of air, assuming that the lower layers are dry enough to permit the passage of this radiation with no more obstruction than that which affects the sun's rays. An upper layer of warm and moist air, 10° C. above surface temperature and 1 meter thick, will radiate 0.0002 radim, but the radiation must be twenty-five times as great if the recovery of heat after a cold wave is to be attributed to direct atmospheric emission. Some effect could no doubt be produced by an indirect process involving layers of considerable depth, but there is no warrant for the supposition that the warm upper currents in the cases cited have an

excess of 10° *above surface temperature.* The existence of warmer air a few meters above the soil which is unduly chilled by nocturnal radiation at the calm center of an anticyclone is not in question here, for this air, although it is so near, being dry, does not radiate enough to prevent the surface refrigeration.

It seems probable that after the descent of dry air at the center of an anticyclone has ceased and unimpeded surface radiation to space has produced the minimum surface temperature of a cold wave, the gradual recovery of heat and moisture by the lower atmosphere is effected principally by the absorption of the sun's rays, by evaporation from the surface, and by the mingling of air from warmer regions, and that any contribution which atmospheric radiation from upper warm layers may give to this recovery of heat is not likely to produce a rise of temperature of more than 1° C. per day.

The power of warm air to radiate must depend largely on its isolation. An upper body of warm moist air, if freely suspended in the midst of dry air, immediately becomes a good radiator, not only by virtue of its high temperature, but because of its containing an especially emissive substance. The radiation, however, owing to the peculiar absorption of its own rays by the moist air, can only proceed through a small surface layer, which soon becomes saturated by the cooling. The great increase of absorption which has been shown to occur at the condensation point of water prevents further cooling by radiation, except in an excessively thin surface shell of cloud, and it is doubtful if any large proportion of rainfall is produced through cooling of moist air by radiation, even in those towering cumulo-nimbi which ascend into dry regions where the radiant effect is greater. While cumulus clouds may be thimble-shaped shells, the typical rain-cloud generates its rain, not by any skin-squeezing process, but by expansive cooling which affects the entire volume of air.

Air radiation must usually proceed more easily upward than downward, because the higher layers are apt to be drier and more transmissive than the lower. Cooling by radiation, although of small moment in the lower air, must be added to cooling by expansion as a cause for the cold of the high atmosphere; and the diminution of absorption of its own radiation by air at great altitudes on account of lessening aqueous vapor, so far compensates for decrease of radiant power at very low temperatures that cooling by air radiation may be effective to the outer limit of the atmosphere, and may prevent the retention of such molecular velocities as would permit the escape of air molecules, except in the very unusual case of the ejection of intensely hot vapor to great heights by volcanic eruptions. The former prevalence of vigorous vulcanism on the Moon has perhaps had more to do with the loss of the Moon's atmosphere than the smallness of its attraction, at least the fact that one or more of Jupiter's satellites exhibit phenomena which are presumably atmospheric, warns us not to place too great faith in the theory that a small planet must necessarily have a relatively small atmosphere. Another cause which has peculiarly favored the loss of the Moon's atmosphere by the escape of individual molecules of high velocity has been the slowness of its axial rotation, which permits an accumulation of heat during the long day until surface temperatures considerably above that of boiling water are attained. (See the author's "Probable range of temperature on the Moon," *Astroph. Journ.*, vol. 8, Nos. 4 and 5, Nov. and Dec., 1898).

The results of the present research prove that within moderate depths of only a few meters the radiation of dry air, purified from carbon dioxide, increases quite uniformly with the depth; that the radiation of a 1-meter layer of purified air at 50° C. and near atmospheric pressure (735 mm.), as compared with one at 0° C., is 0.00068 radim, representing a transformation and transfer of thermal energy of 0.00068 small calories every second through each square centimeter of limiting surface; that the radiation of a like depth of carbon dioxide at the same temperature is three and one-half times that of air, or 0.00238 radim, which is very nearly a maximum for this temperature, further increase of the radiant depth being unattended by a corresponding addition of radiant energy, showing that equilibrium between radiation and emission has been almost reached at this depth; that the radiation from a layer of steam 5 feet deep at one-sixth of atmospheric pressure is two and one-half times that from a like body of dry air at temperatures near the boiling point of water, and eight-tenths of the radiant emission from the black solid body; while for smaller depths the radiant power of water-vapor is relatively greater, a steam jet of small

dimensions radiating over four times as strongly as one of air, a ratio which would doubtless have been considerably greater if the air had been perfectly dry.

There appears to be no reason to doubt that the radiation of a moderate depth of homogeneous air at a given temperature depends on the product of the depth by the density, and remains the same when depth and density vary inversely; but the absorption of a given mass of aqueous vapor has been found to be smaller when distributed through a large volume of air than when concentrated.* The phenomena are conditioned by molecular relations. Reciprocal variation of depth and density does not change the number of molecules which are engaged in the radiant transaction in a homogeneous medium; but dilution by another substance involves a partition of energy among molecules whose radiant and absorbent properties are dissimilar.

As an absorbent of terrestrial radiation aqueous vapor is very much more efficient than any other atmospheric ingredient; but as radiators when in large masses, the substances which compose the atmosphere do not differ as widely as might be supposed, and the position of chief radiant may be assumed in turn by either aqueous vapor, carbon dioxide, or the permanent gases, according as the depths and temperatures of the emissive and absorbent layers change.† The depth of gas which gives maximum radiation at short range is an insignificant quantity compared with atmospheric dimensions, and radiation from either the atmosphere of the Earth or the solar chromosphere is a superficial phenomenon, even when the masses of heated gas measure thousands of miles in thickness. The fineness of the chromospheric lines in the solar spectrum, although the shifts of the Fraunhofer lines indicate pressures of many atmospheres at the base of the chromosphere, is a sufficient demonstration that only the outer layers radiate. If the emission proceeded also from the depths of the chromospheric mass, the lines of hydrogen and some other elements would be greatly widened; and if the Earth's atmosphere radiated unimpeded throughout its depth, its thermal changes and its radiant effects would be enormous. Instead of this, we find the atmosphere playing the part of a conservator of thermal energy, and must gratefully admire the beneficent arrangement which permits the Earth to be clothed with verdure and abundant life.

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* See p. 94.

† This statement can not be absolutely verified, because the dimensions of my apparatus were insufficient to give the maximum radiation for pure air, but it is strongly indicated by the curves and on theoretical grounds.

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